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XENON-133 SPIROMETRY EMPLOYING MULTIPLE DETECTOR SPECTROMETRY WITH COMPUTER ASSISTED DATA ANALYSIS

by

© LEONALD WAYNE FRIEDENBERG

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled XENON-133 SPIROMETRY EMPLOYING MULTIPLE DETECTOR SPECTROMETRY WITH COMPUTER ASSISTED DATA ANALYSIS submitted by Leonald Friedenberg in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering.

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ABSTRACT

This thesis describes a radioactive tracer method for detailed study of the function of the human lung. Regional ventilation and perfusion are investigated using a specially designed bed which supports the patient and the gamma ray scintillation detectors. The bed is designed to facilitate routine hospital studies as well as continuing research in this field. An electronic device has been designed to operate in conjunction with a spirometer to aid in tidal respiration monitoring. Analysis of the experimental data is carried out with the aid of a laboratory digital computer and results are made available to the clinician with a minimum of elapsed time.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

The human lung is one of the most abused organs in the modern world. Smoking and all forms of air pollution constantly attack these delicate tissues. It is not surprising, therefore, that much effort is being put into the investigation and treatment of lung ailments. Since the lungs are rather large organs by volume, it is advantageous to the clinician not only to determine the nature of a lung disorder, but also to determine which part of the pulmonary system is affected. To meet this requirement, a technique for the study of regional pulmonary function has been developed. This measurement technique considers each lung as consisting of four parts and provides a functional comparison among these parts. Regional studies can indicate whether or not a disease is spreading or show the effect of a particular medication. With this incentive for regional studies of the pulmonary system we briefly describe one possible way of implementing investigation.

The apparatus consists of 16 NaI(Tl) scintillation detectors which are mounted in lead collimators on a specially designed patient support system. The information gathered by these detectors is amplified, analyzed, and then stored in a 1600-word ferromagnetic core memory. An interface between this memory and a seven-track digital tape recorder allows permanent storage of the information for subsequent computer analysis.

Many less elaborate techniques have been used for the study of the pulmonary system. Conventional clinical techniques such as bronchospirometry and radiography do not provide the physician with all of the information which he requires. For additional information, researchers have explored the possibilities of using radioisotopes for more detailed lung studies. Macro-aggregated forms of Technetium-99m and Iodine-131

have been used to study lung perfusion. For ventilation studies, the isotopes of many of the inert gases as well as radioactive forms of oxygen, nitrogen, and carbon dioxide have been tried. We confine our study to the use of gaseous Xenon-133 which is by far the most popular radioisotope in use at present.

One of the reasons for the popularity of Xenon-133 is its low radiation dose to the patient[1]. Its half-life of 5.27 days and relatively low cost of production also contribute to the list of advantages for using Xenon-133 as a radioactive tracer for studies of lung function.

To gain additional information during the investigation of ventilation, data is also collected from a spirometer[2] by means of an A to D converter and an on-line digital computer. Certain of the ventilation studies require individual breath-by-breath analysis and to facilitate this, an electronic end-of-breath sensor has been designed and constructed. A detailed description of the apparatus and the data analysis will be found in later chapters.

It must be emphasized at this point that, although the theory of operation and the apparatus itself is relatively complex, the clinical procedure must be kept as simple as possible. The time taken for any given test should be reasonably short and patient discomfort must be kept at a minimum. The results obtained must be reliable and easy to interpret by a physician without requiring him to possess a detailed knowledge of the appartus used. The following chapters attempt to provide solutions to such problems.

---

1 Matthews, et al

2 Godart Pulmotest

CHAPTER 1

HISTORICAL REVIEW

In order to better understand the aims of the present study, we will briefly review some of the physiological aspects of the lung. Each lung consists of a capillary bed surrounding tiny sacs of air called alveoli. Gaseous exchange between the blood and the air takes place by the process of diffusion through the alveolar membrane. If a particular region of lung tissue is either poorly supplied with blood or underventilated, an abnormal condition exists. To obtain a clearer picture of these abnormalities we need to find a way to measure regional ventilation and perfusion of the lungs. The use of radioactive tracers provides a relatively simple means of accomplishing this.

Studies of lung function with radioactive gases originated in 1955 when Knipping et al introduced the use of Xenon-133. Early studies were also done by Valentin, Venrath, and Markou in 1956; and Knipping, Bolt, Valentin, Venrath and Endler in 1957 and 1958. All of these studies dealt with the measurement of ventilation only. Later in 1962 Ball et al used Xenon-133 to measure perfusion and regional lung volume as well. The quality of the equipment used in these studies as well as the procedure of data collection and analysis left room for considerable improvement.

During the development of Xenon-133 spirometry, other radionuclides were also investigated. Oxygen-15 was used both as oxygen gas and as carbon monoxide and carbon dioxide. The investigators included Dyson, Hugh-Hones, Newbery, and West in 1958; Dollery et al in 1960; and West in 1962. The main disadvantage with Oxygen-15 is its very short half-life of two minutes. Hence, a cyclotron or other accelerator must be

located at the site of the investigation. Xenon-133 with a half-life of 5.27 days circumvents this problem.

Static studies of pulmonary perfusion have also been carried out with substances such as Iodine-131 macro-aggregates of human serum albumin. Wagner, Sabiston, McAfee, Tow, and Sterm; and Lopez-Majana, Chernick, Wagner and Dutton are two groups who published their results in 1964. Static studies permit the use of much simpler apparatus. For example, a rectilinear scanner can be used to provide a static picture of the distribution of radioactivity. However, in general, dynamic lung function studies are of greater interest to the clinician.

Some of the more recent dynamic studies were carried out by Ball et al (1962) in Montreal, Miorner (1968) in Sweden, and Miller (1970) in Houston. To the knowledge of the author, none of the above groups have investigated the merits of detailed computer analysis of their results. Paper chart recorders have been used extensively to produce graphical output. Measurements from these graphs are taken to represent the parameters of the lung function. However, the very small size of the graphs makes accurate measurements almost impossible. Also, the probability of human error is much greater with this technique. Computer analysis of data is one of the techniques described in this thesis to improve the accuracy and reproducibility of radiospirometry. In order to examine other inovations of the technique described in this thesis we will briefly review some of the other shortcomings of the methods used by the investigators noted above.

In Miorner's (1968) investigation, patients were studied in a supine position whereas Ball (1962) and Miller (1970) employed the upright (sitting) position. To permit comparative studies as well as to accommodate all types of patients, the apparatus described in this thesis was designed to

operate in both of the above positions as well as lateral and inclined positions. Miorner's group studied only two areas per lung, whereas other groups have used up to eight areas per lung. (The study with 16 detectors investigated lung ventilation only.) It was decided to use eight lung regions (four per lung) for the present study. These regions correspond to those described by Miller (1970) et al. Most of the earlier studies employed detectors placed on the dorsal side of the chest. An exception is Heckscher et al (1966) who used detectors on the ventral side. Very few groups have used front-back paired detectors. Dyson, Hugh-Jones, Newbery and West tried paired detectors in connection with their Oxygen-15 studies in 1958. Later in 1962 Dollery et al used 2 sets of paired detectors with Xenon-133 as tracer. Mannel et al (1966) used 6 pairs of detectors.

In order to reduce the number of detectors required, a technique of scanning was investigated by Dollery and Gillam in 1963. Scanning imposes many limitations. Basically, the resultant profile obtained by scanning is static rather than dynamic in nature. For the present study, 16 fixed detectors were used. This allowed dynamic studies with eight lung regions, each of which was viewed by two detectors. One of the earlier complaints regarding multiple detectors was the very large amount of data to be analyzed. By introducing a computer based data acquisition and analysis technique, this disadvantage has been overcome.

The introduction of the scintillation camera in 1958 by Anger produced considerable interest in the study of pulmonary function, but its usefulness was limited because the field of view was too small to adequately cover all parts of both lungs simultaneously. The subsequent development

of the "diverging" collimator[3] provided a solution to this problem. However, the problem of excessive data rates coupled with poor sensitivity has discouraged the development of advanced camera techniques. Multiple detector systems employing digital data acquisition are generally less costly than camera systems, and their increased efficiency and better time resolution makes them more suitable for pulmonary function studies. In addition, a much lower dose of radioactivity is required to achieve comparable results. The purpose of the present study is to increase the accuracy, simplicity, and feasibility of earlier multiple detector radiospirometry techniques by introducing more advanced data collection apparatus and utilizing a digital computer to deal with the vast amount of ensuing data.

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3 Nuclear-Chicago Corporation

CHAPTER 2

SYSTEM DESIGN

The system described in this thesis was designed to exploit the advantages of digital data acquisition to gather information from a radioactive tracer gas which is used to indicate the distribution of ventilation and perfusion. In order to accomplish the required spectrometry, a patient support system containing radiation detectors was designed and constructed. Many of the components for the data acquisition system were commercially available. Other parts were either not available, or not well suited to our needs, and we had, therefore, to design and construct our own prototypes.

This chapter is divided into four sections dealing with the four main aspects of the system. The first section deals with the design of the patient and detector support unit. The theory behind the scintillation spectrometer system is discussed in Section B. Section C explains the spirometric requirements and capabilities which were designed as part of the overall data collection system. The last section deals with the signal processing as well as the actual data handling and storage facility.

A. PATIENT-DETECTOR SUPPORT SYSTEM

A logical place to commence the discussion of the apparatus would be that part which is closest to the patient being examined. Following are some of the design criteria for the patient-detector support system.

1. The bed must safely and comfortably accommodate any patient.
2. Tests must be possible in any of the following positions:
    a. sitting upright (See Figures 2-1 to 2-3)

b. supine (See Figure 2-4)

c. prone

d. lying lateral, on either side (See Figure 2-5)

e. any angle of inclination between the supine and upright positions.

3. Detectors and collimators must be fixed to the bed to ensure accurate alignment.
4. The position of the front detectors must be easily adjustable to accommodate patients with varying chest thicknesses.
5. For the lateral position the detector assemblies must be swung to the sides.
6. The front detector assembly must swing open to facilitate patient entry and exit.
7. The height of both detector assemblies must be adjustable when used in the upright position.

The support system was constructed on a rigid stainless steel box frame (See Figure 2-1). Four locking castors permitted the entire unit to be easily moved. The moveable part of the bed which supports the patient's chest and the 16 detectors was fitted with counterweights to allow easy changes in position. Without counterbalancing, the moveable upper half of the bed would have been unmanageable. A foot-operated locking device was constructed to secure the moveable portion at any desired angle of inclination. This allowed 90 degrees of adjustment from the supine to the upright position.

The detectors and lead collimators were mounted on aluminum sub-assemblies, which were supported by rigid stainless steel rods mounted on oversized bearings. These bearings were secured to the moveable part

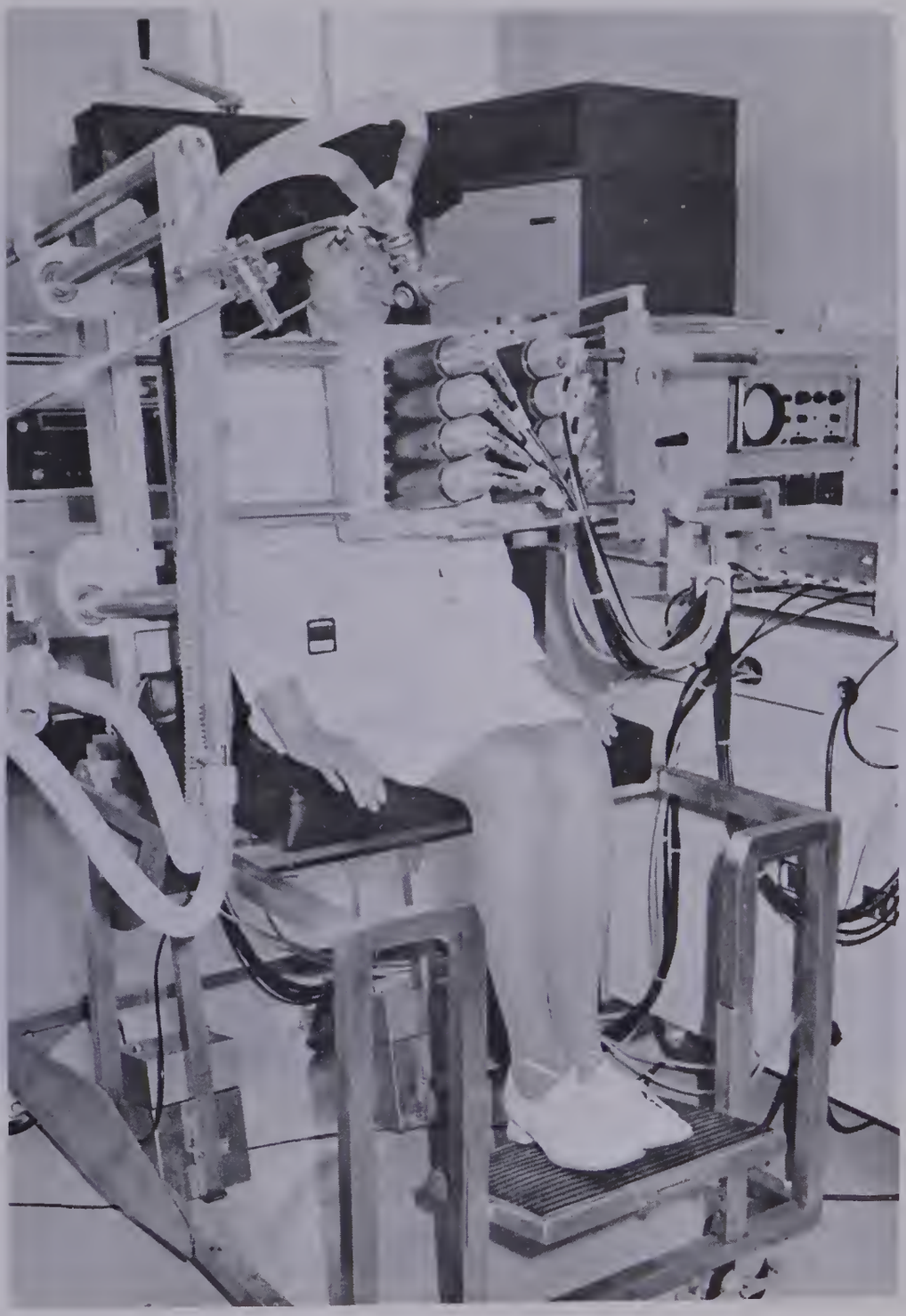


FIGURE 2-1

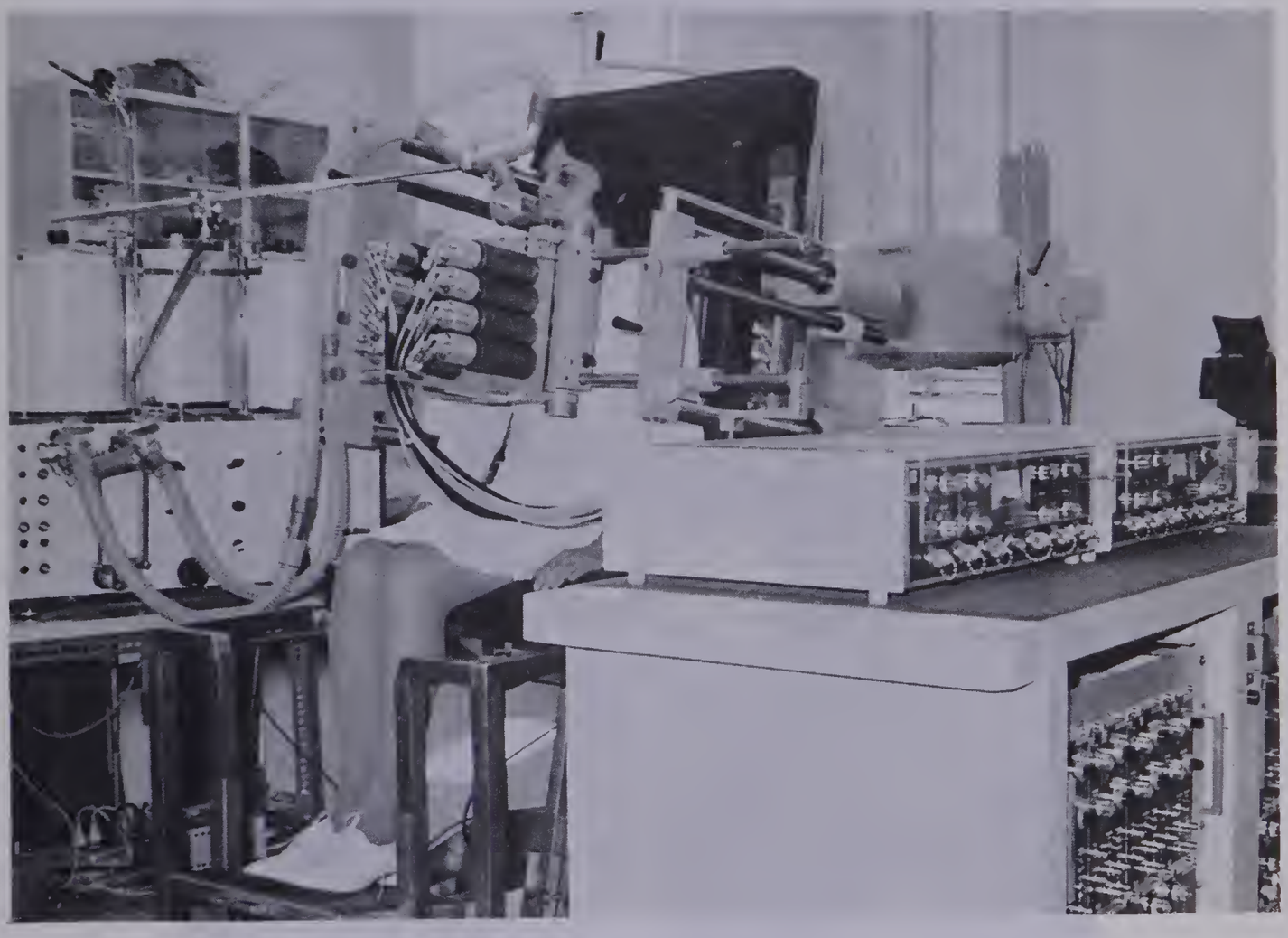
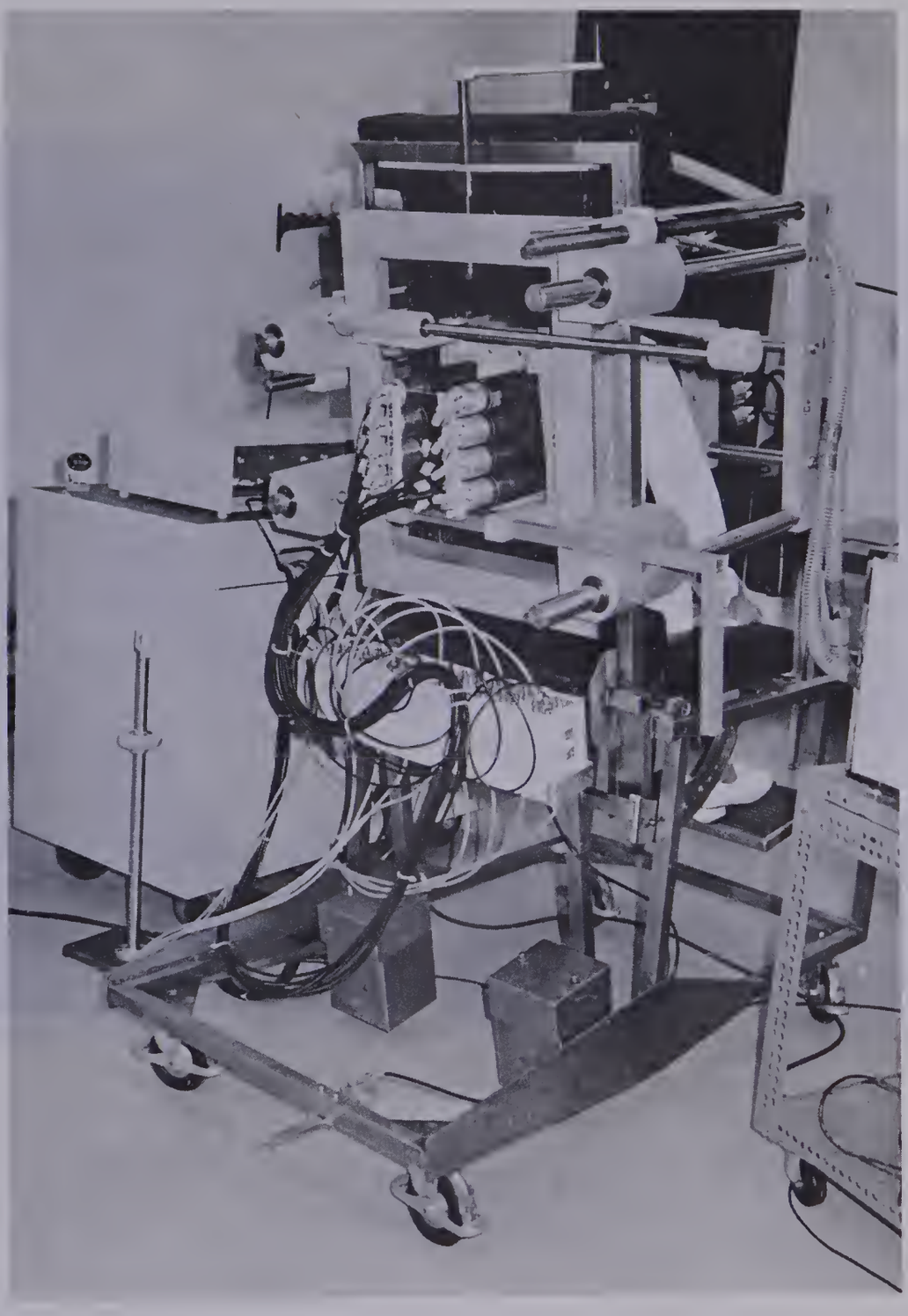


FIGURE 2-2



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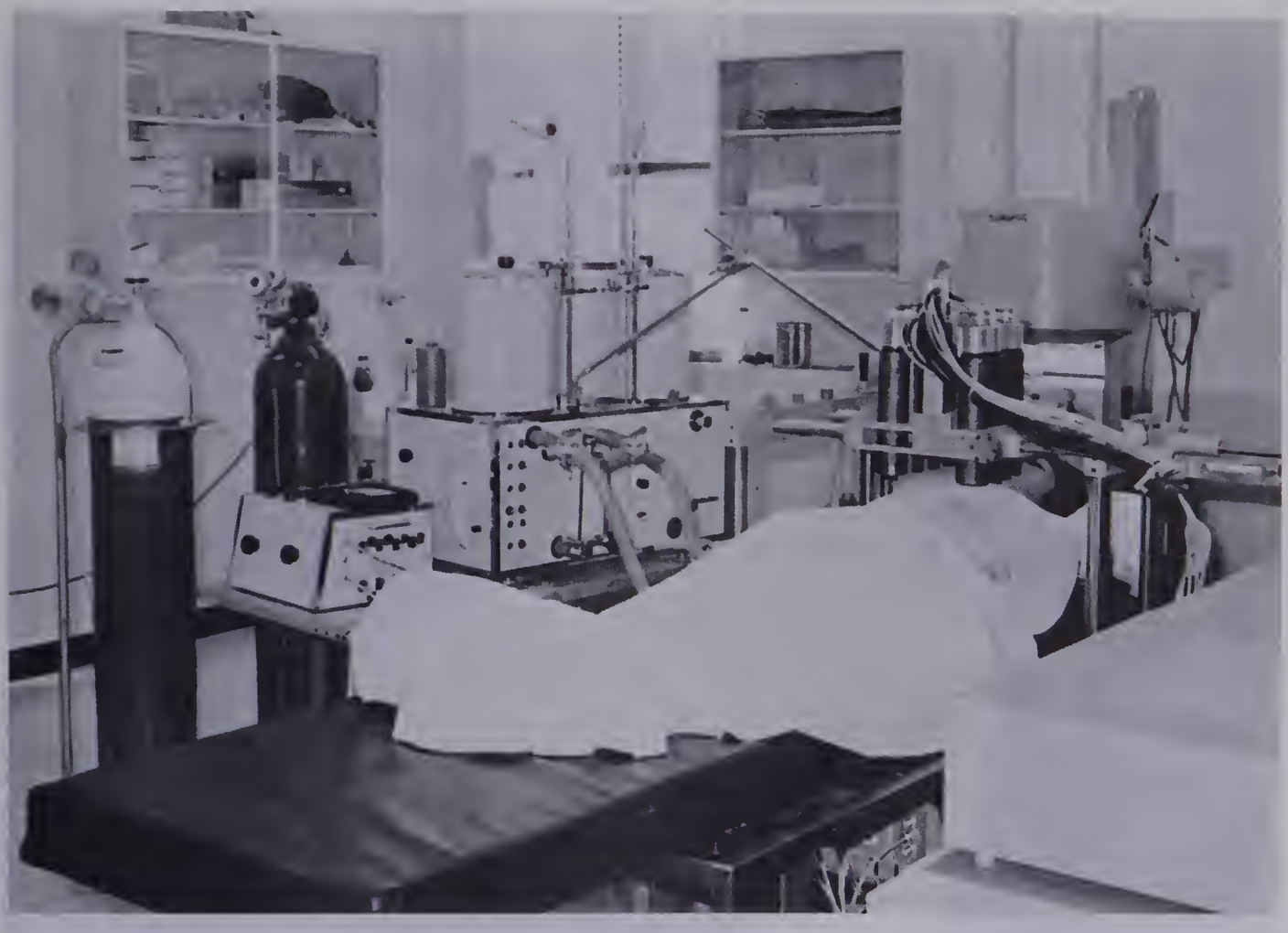

FIGURE 2-4

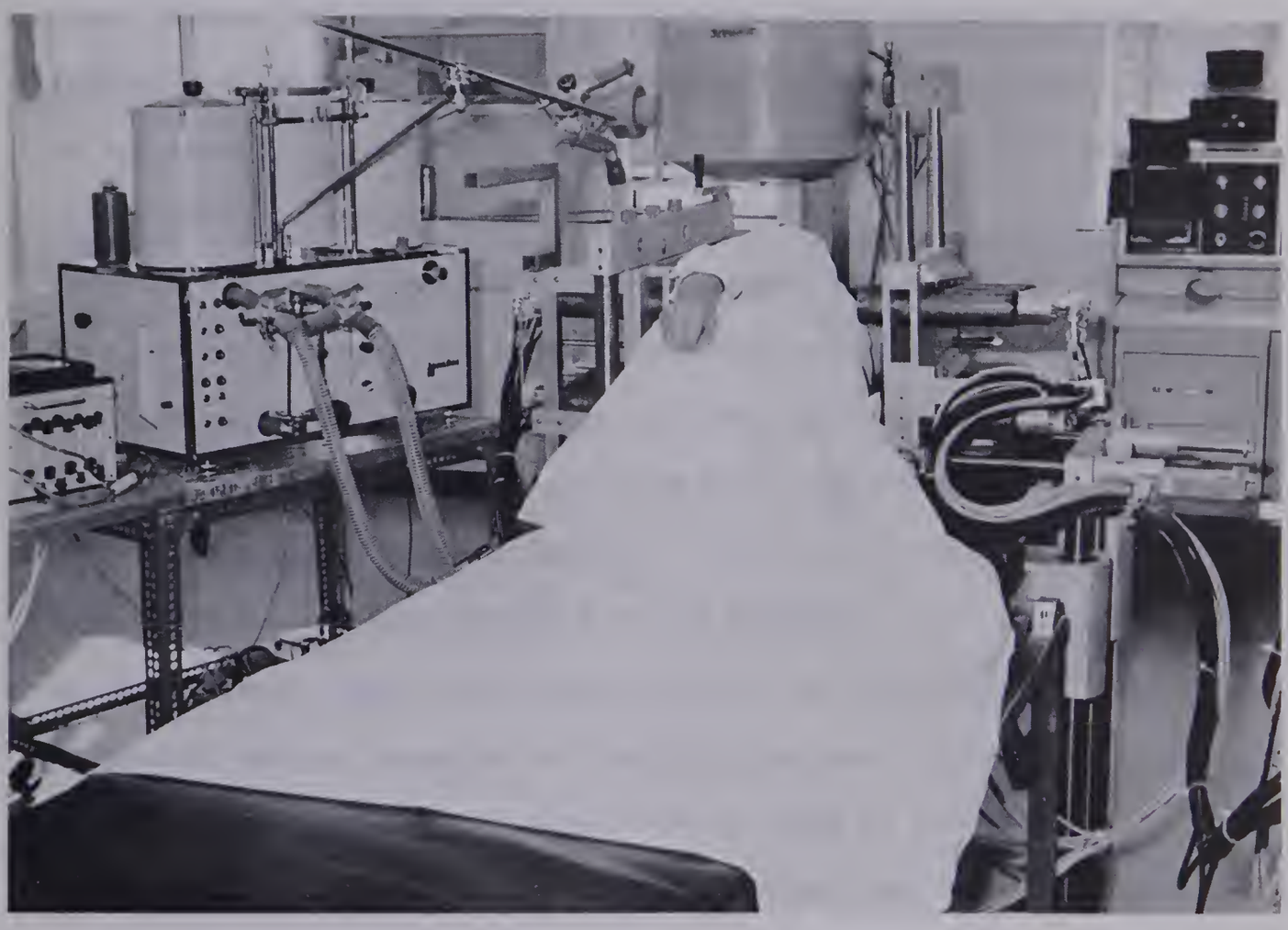

FIGURE 2-5

of the bed so that the detector-to-patient position remained constant at any angle of inclination. To facilitate patient entry the front detector subassembly was made to swing open and slide to one side. Thumbscrew locks were used to secure this assembly in both the open and closed positions.

Because of the considerable variation in chest thickness among patients a simple screw crank adjustment was provided to vary the distance between the front and rear detectors. The detectors themselves remain in a fixed position relative to each other in all cases. That is, no adjustment is provided for varying the configuration of detectors.

Lateral orientations of the patient are studied by first placing the moveable portion of the bed in a horizontal position. After this, the rear set of detectors are swung to one side and secured to one half of the frame which normally supports the front detectors. For the lateral position the front detectors are rotated 90 degrees and moved to the side of the bed opposite the new location of the rear detector subassembly. Again, adjustments were provided to fit different chest thicknesses as well as left-to-right positioning (relative to the patient). This latter adjustment was not required for the other patient orientations because the patient could be easily moved left or right on the bed.

A foam rubber pad covered with black vinyl was designed to support the weight of the patient comfortably in all possible orientations. To protect both the detectors and the patient, without appreciably altering the operation of the rear detectors, a plexiglass cover was fitted in the center of the moveable part of the bed.

When the patient-detector support system is used in the upright position, accurate vertical location of the detectors is important. A screw crank is provided for this height adjustment and a small lamp is

used to project a beam of light on the sternal notch of the subject. The lamp also assists in lateral alignment. Because immobility of the patient is important during all tests, the light beam provides a simple and accurate means of frequently checking the position of the subject.

Now that we can understand the capabilities of the patient-detector support system let us examine the theory of spectrometry and the use of radioactive tracers which are employed by this system.

B. SPECTROMETRY

In Chapter 1 we explained the need for measuring regional ventilation and perfusion. The use of radioactive tracers was mentioned briefly. This section reviews the operation of a gamma ray spectrometer. Figure 2-6 shows a diagram of a single detector[4].

Each scintillation detector consists of a one-inch diameter, 1/2-inch thick, Thallium activated, sodium-iodide crystal (the scintillator). A gamma ray produces a minute flash of light (scintillation) via the "photo-electric effect" upon interaction with the crystal. The direction of incidence of the gamma particle is not important. The efficiency of the crystal is determined largely by its geometry. Half-inch thick crystals provided adequate efficiency for our studies.

All sides of each crystal except one are coated with an extremely good reflective surface to increase the optical coupling efficiency. The uncoated surface is coupled through a light guide to the cathode of a ten-stage photomultiplier tube. In the photomultiplier, an electron is emitted from the cathode whenever it is struck by a few photons. The successive dynodes provide sufficient gain (of the order of 10^6) to

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4 Harshaw Chemical Company: Integral line detector, type 4S2-X

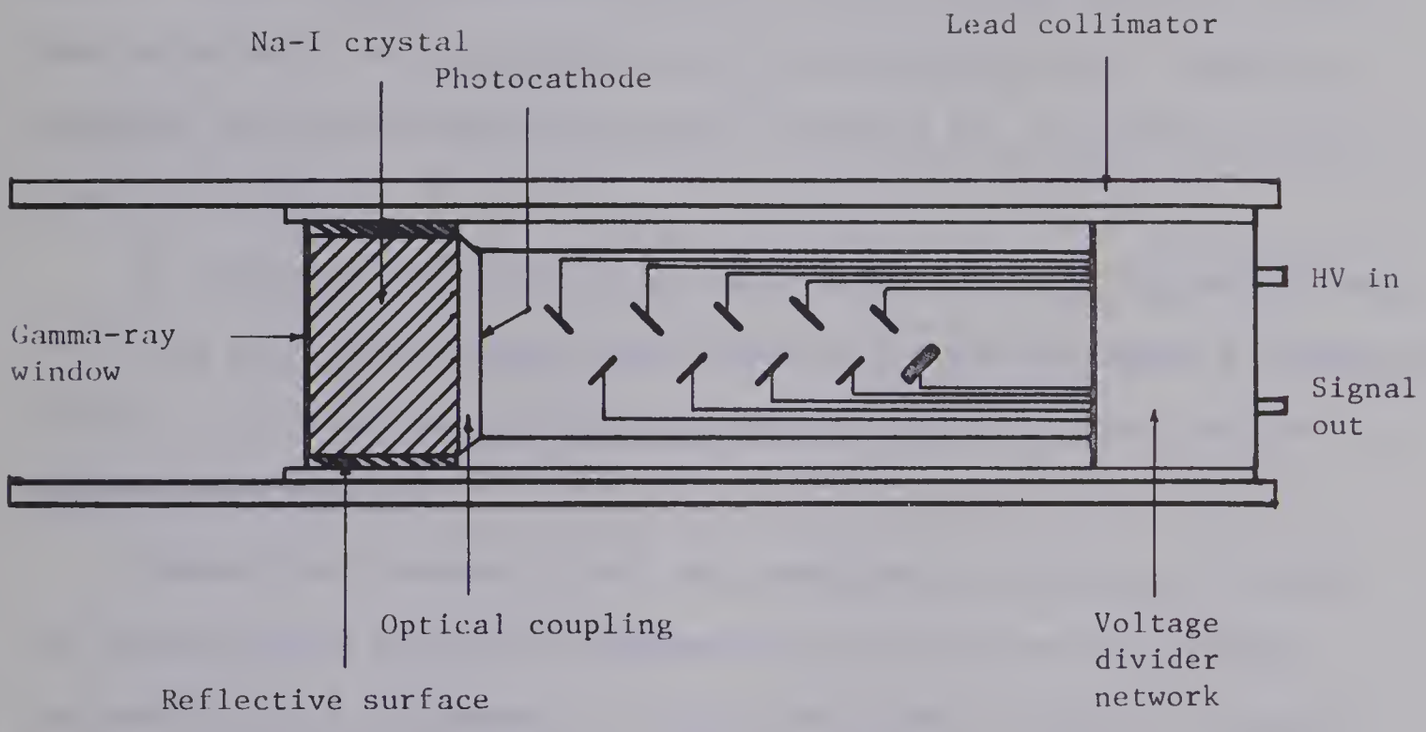

FIGURE 2-6

DIAGRAM OF SCINTILLATION DETECTOR

produce a current pulse at the anode for each incident gamma particle. The crystal, optical coupling and photomultiplier are encased within a light-proof housing and together they form a scintillation detector.

The photomultiplier tubes require successively increasing positive potentials on successive dynodes. The correct voltages are supplied through a resistive voltage divider network on each tube. Since the gains of these tubes depend upon the total high voltage supplied, individual adjustments were provided for the 16 photomultipliers. Four main supplies[5] and four distribution panels[6] provided the necessary high voltage requirements.

By inserting a resistor in the anode circuit of each photomultiplier, an output pulse with voltage proportional to the incident gamma ray energy was derived. The analysis of this pulse height becomes the basis for the spectrometry involved.

Because each detector is not very sensitive to direction of origin of incoming gamma particles, some method of focusing must be utilized. Cylindrical lead collimators, 1/4" thick were used to narrow the field of view of each detector to the shape of a cone[7]. With one posterior detector and one anterior detector for each region of lung, the combined section of tissue viewed approximates a cylinder as shown in the next chapter.

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5 Nuclear-Chicago Model 27452

6 Nuclear-Chicago Model 23401

7 See Chapter 3 for illustrations of collimator response

C. SPIROMETRY

Conventional spirometry for the measurement of pulmonary function parameters has been in regular clinical use for many years. Radiospirometry, on the other hand, is relatively new. All forms of pulmonary function studies which employ a radioactive tracer are classed as radiospirometric studies. We confine our discussion of spirometry to that which is required to measure regional ventilation in the human lung.

Before delving into the mechanics of the spirometry used, let us review some of the elements of pulmonary physiology. The human lung can be considered to be a system of tiny inflatable balloons, called alveoli, each surrounded by a capillary filled with blood. The alveolar membrane allows gaseous exchange between the air inside the alveolus and the blood in the capillary. In a normal situation, oxygen required to sustain cell metabolism diffuses into the blood, and the respiration by-product carbon dioxide diffuses out of the blood. When Xenon-133 is used as a radioactive tracer, it also diffuses freely through the alveolar membrane, but because of the limited solubility of Xenon-133, most of it resides in the gas phase within the alveoli. Only a small percentage of the Xenon-133 is carried to other body tissues in the bloodstream.

Included in each lung are various interconnecting arteries and veins as well as a vast network of air passages called bronchi. Air which remains within these bronchi and larger bronchial tubes does not come into contact with the blood and provides no useful gaseous exchange. Hence, it is termed "dead space". In calculating the amount of air reaching the alveoli (true ventilation), one must take into account this dead space volume as well as the volume of the trachea and the mouthpiece connected to the spirometer.

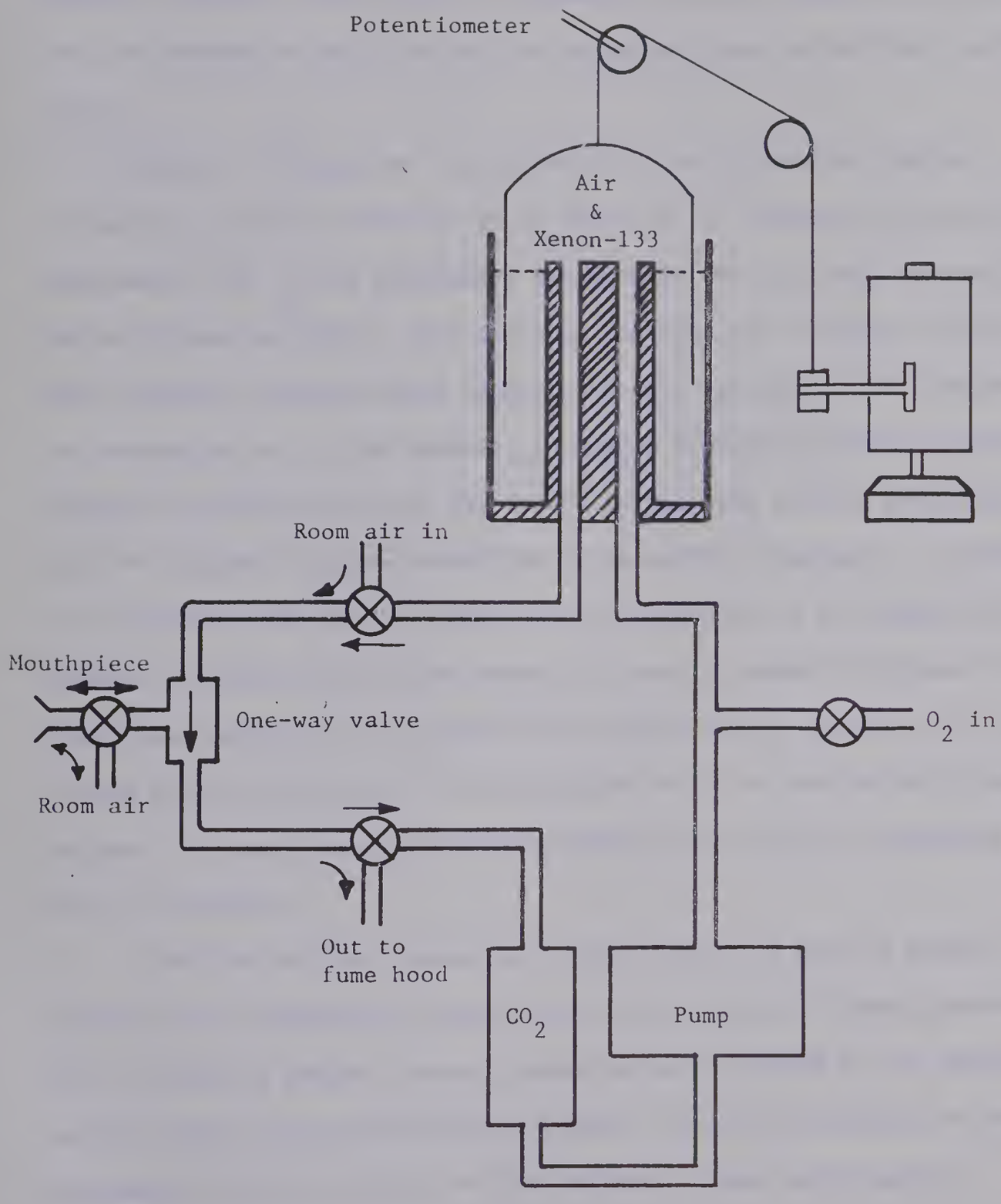

FIGURE 2-7

SPIROMETER CIRCUIT FOR ROUTINE TESTS

The present technique for the study of ventilation has been developed from principles set forth by earlier investigators[8]. A later chapter examines a new method for measuring regional ventilation, but for the present we will look at the spirometry used in the basic set of tests.

Figure 2-7 shows the circuit used for equilibration studies. Air containing a small concentration of Xenon-133 is circulated from the left spirometer bell to the mouthpiece and back to the left bell through a carbon dioxide absorber. The absorber consists of a cylinder filled with baralime crystals which remove excessive carbon dioxide from the recirculating air in the system. An oxygen stabilizer system allows oxygen to transfer from the right bell to the left bell to compensate for the subject's oxygen uptake due to metabolic processes. It should be noted here that the left bell of the spirometer is the active one, whereas the right bell serves merely to store a supply of oxygen. The stabilizer consists of a solenoid valve which allows oxygen to be transferred to the left bell of the spirometer as it is used by the breathing subject. A constant volume sensing unit on the left bell regulates the rate of transfer.

A helium analyzer connected to the circuit is used to measure the amount of air remaining in the alveoli at the end of a normal expiration. This is done by adding a known concentration of helium to the spirometer at the start of the equilibration process. When the contents of the spirometer and the contents of the subjects' lungs have reached

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8 Miller, et al (1970)

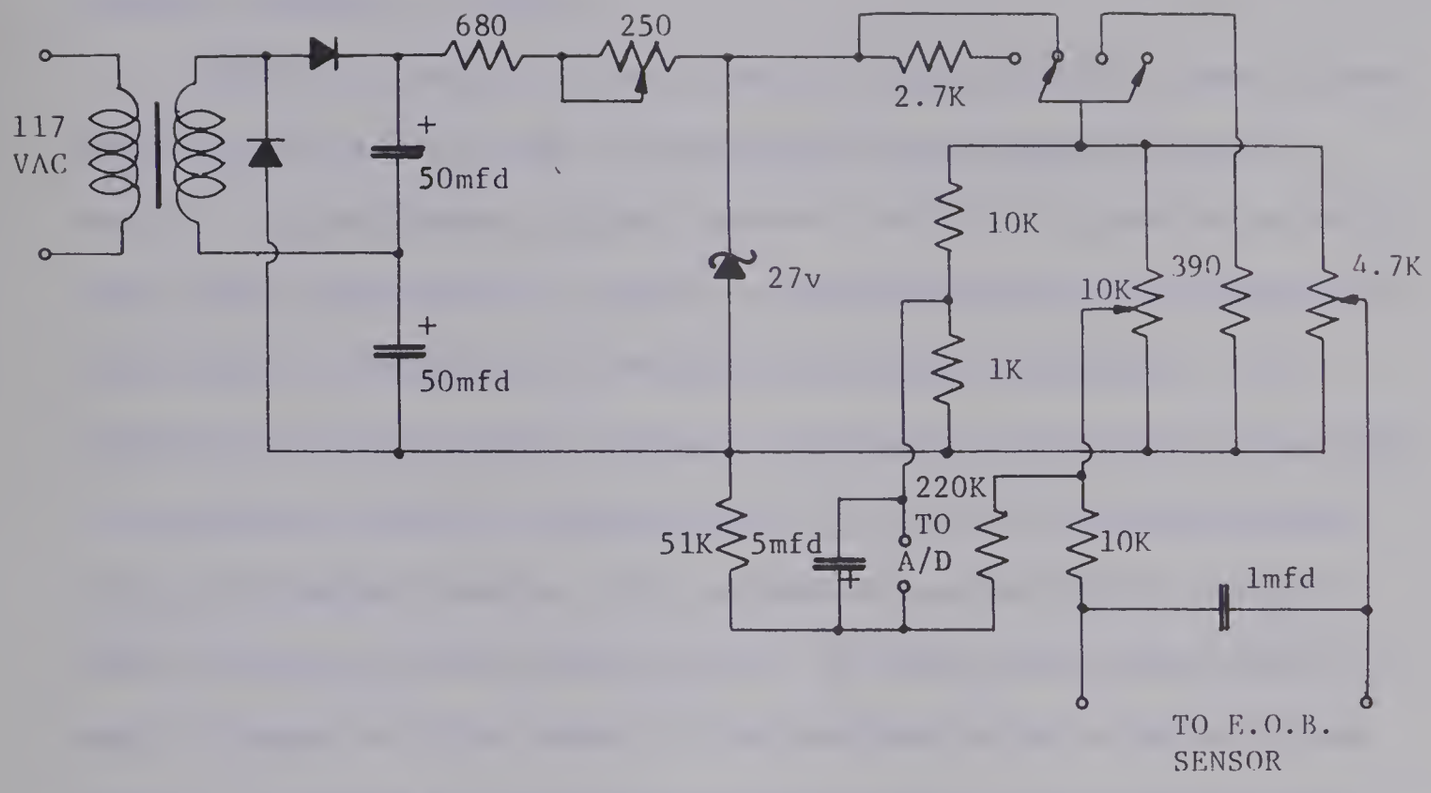

FIGURE 2-8

SPIROMETER ANALOG OUTPUT CIRCUIT

equilibrium, the drop in helium concentration is measured by the helium analyzer and a simple calculation is performed to determine the volume of air contained in the lungs[9]. This volume is called the functional residual capacity (or FRC).

During the course of a test, the left spirometer bell moves up and down to indicate the volume of air inspired and expired with each breath. A potentiometer circuit connected to the bell provides an analog signal which represents the subject's breathing pattern (See Figure 2-8). This signal is connected to two auxillary pieces of equipment. To measure and calculate tidal volumes, the signal is connected to the input of an analog to digital converter which is part of the Bioengineering laboratory computer system. The computer is used on-line to compute tidal volumes and minute ventilations. The term "minute ventilation" is used to denote the total amount of air inspired during a period of one minute. A listing of the Fortran program used for these computations can be found in Appendix III.

The second use for the analog signal from the spirometer is for the purpose of individual breath definition. The reasons for using this method are outlined in the chapter on multiple single breath studies.

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9 See Godart Pulmontest operating manual

D. SIGNAL PROCESSING

In Section B, it was explained how each gamma-ray produced a voltage pulse at the anode of a photomultiplier tube. These pulses are negative-going, with amplitude proportional to the energy of the incident gamma radiation. The energy of the gamma-ray is now in the form of an electrical pulse which must be amplified and analyzed before serving any useful purpose (See Figure 2-9).

The pre-amplifiers[10] which are mounted on the detector support assembly perform several functions. First they combine the outputs of two detectors to form a composite signal representing a front-to-back cylindrical section of the subject's chest. Other functions include a change of impedance from 500,000 ohms to 50 ohms and a small amount of linear voltage gain. The output pulse from the pre-amplifiers has a fixed risetime and decay characteristic which is independent of the shape of the input pulses. The remaining voltage gain required is provided by a rack-mounted RC pulse amplifier[11]. At this point, the incoming pulses must be analyzed. That is, we wish to exclude all pulses which do not have an amplitude corresponding to the gamma-energy of the Xenon-133 source. The function of each of the single channel pulse height analyzers[12] is to produce a constant amplitude output pulse for each input pulse whose height falls between the preset limits.

In all, there are 8 pre-amplifiers, 8 RC amplifiers, and 8 single channel analyzers in use on this system. This provides a signal

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10 Nuclear Chicago Model 23801

11 Nuclear Chicago Model 27001

12 Nuclear Chicago Model 27352

corresponding to each of 8 regions of the human lung. From the analyzers the pulses are routed to an 8 input multiplexor which stores them in their proper places in a 1600-word memory[13]. The 1600 words of memory are subdivided into 8 groups of 200 words. Normally, during a test we would store the total number of pulses occurring in a predetermined time interval into words 1, 201, 401,...etc., from region 1, 2, 3,...etc. of the lung. Then, during the next interval of time, the pulses would be counted in words 2, 202, 402,...etc. This allows us a time sequence of 200 points for each area of the lung.

The number of pulses counted in such a manner corresponds to the concentration and volume of the radioactive gas "seen" by the appropriate detector pairs during the time interval. Accordingly, if the subject breathes air tagged with Xenon-133, we can measure the amount of air reaching a given region of lung. If the Xenon-133 is injected into the bloodstream, we can measure the amount to which each area of lung tissue is perfused with blood.

In order to use the information stored in the 1600-word memory, it is transferred to a 7-track digital tape recorder[14] and stored on 1/2" magnetic tape for subsequent analysis by computer. The 1600-word memory can be set up to transfer the information to the tape automatically upon receipt of a signal from the end-of-breath sensor. This mode of operation is used for breath-by-breath studies. (See Chapter 6) The time required for this transfer of information is approximately 400 milliseconds. During this time, all incoming pulses are rejected, but the amount of information lost is small due to the short time involved.

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13 RIDL Model 24-3

14 Hewlett-Packard Model 2020B

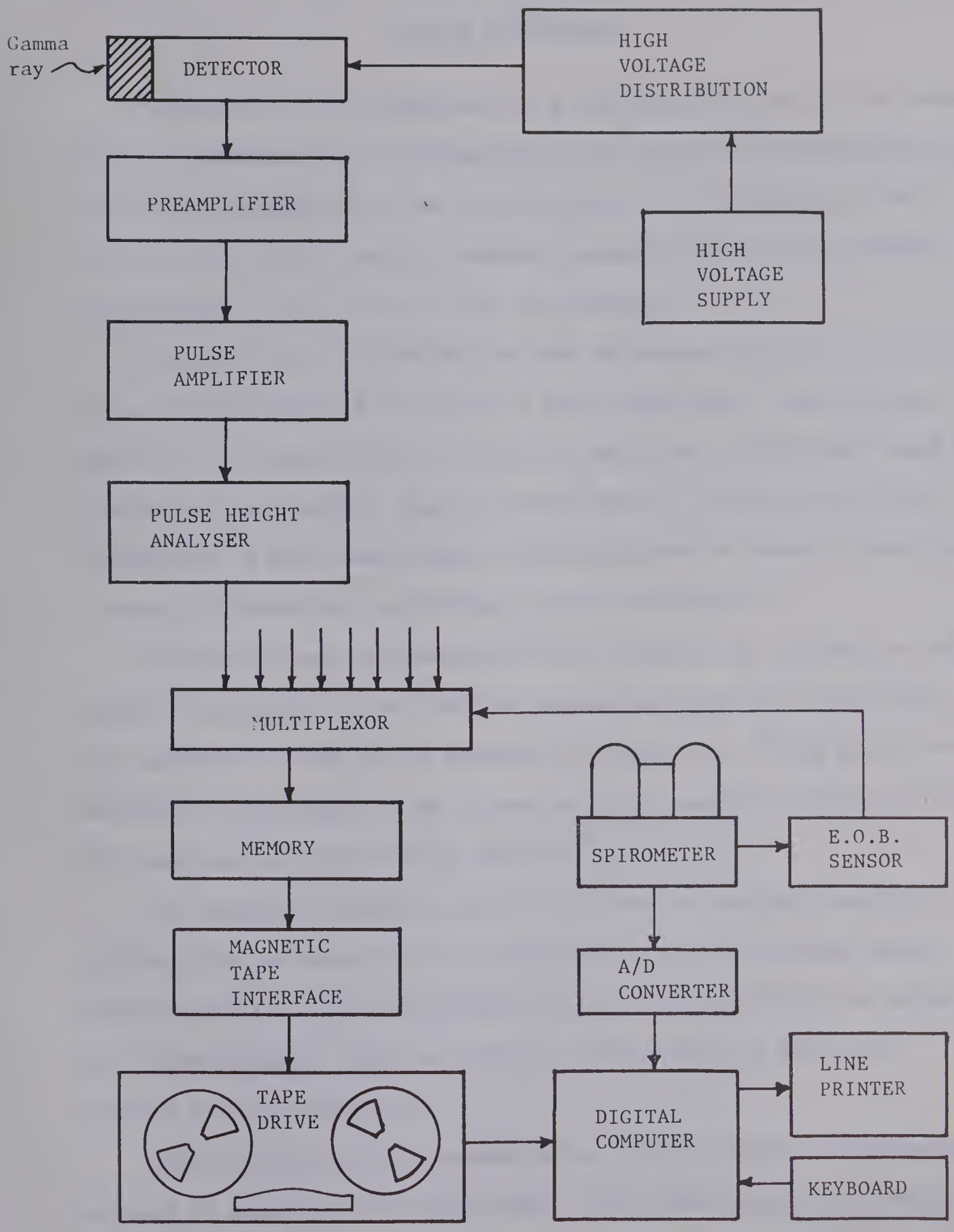

FIGURE 2-9

BLOCK DIAGRAM OF SIGNAL SYSTEM

CHAPTER 3

SYSTEM CALIBRATION

Calibration of the apparatus was a very important part of the investigation. Components were selected which best suited the application with a careful consideration of the cost involved. The 16 detectors were chosen so that their spectral response characteristics were reasonably well matched. (See Figure 3-1 for photographs.)

Initial system calibration involved adjustment of the gain of each of the 16 photomultipliers and the 8 pulse amplifiers. Fixed voltage gains of 37 dB were chosen for the pulse amplifiers. (This was found to provide the best overall signal to noise ratio.) To facilitate gain calibration, a test source holder was constructed to correctly position a Xenon-133 source in front of any of the 16 detectors.

The gain of each photomultiplier was adjusted (by varying the value of the high voltage to the tube) to produce an output of 7 volts from the amplifier for the 81 Kev gamma-ray of Xenon-133. These pulses were measured at the output of the respective pulse amplifiers with the aid of a multichannel pulse height analyzer[15].

The photographs shown in Figure 3-1 show the spectral response of the detectors as measured by this analyzer. The high voltage adjustments provided on the distribution panels were used to vary the gains of the photomultiplier tubes so that both energy peaks of Xenon were matched in all 16 detectors.

After the gains of all detectors had been adjusted, the system was allowed to stabilize for several days. The system gains were completely

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15 RIDL Model 24-2

rechecked at this time. For reasons of gain stability, the entire system remains powered 24 hours per day.

When the amplifiers had been satisfactorily adjusted to produce output pulses which were within the range of the analyzers, the upper and lower discriminators were calibrated. The multi-channel analyzer, used in a time sequenced mode, was employed to obtain a spectrum corresponding to the range of the threshold adjustment of the single channel analyzer. Photographs of these spectra are shown in Figure 3-2. The analyzers were then adjusted to accept the 81 Kev energy level of Xenon-133 and to reject noise, x-rays, and other unwanted pulses. This completed the electrical calibration of the system. The photomultiplier gains are checked daily to ensure accuracy.

The next stage in calibration involved the determination of collimator efficiency. To do this, a set of iso-response curves was plotted. A Xenon-133 point source was counted in a variety of positions on a matrix, first with one detector and then with a pair of detectors. The results of these studies are shown in Figures 3-3 and 3-4. The original design of the lead collimators proved to be adequate.

To determine the effect of Compton scattering, the collimation studies were repeated with the Xenon-133 source immersed in a water filled container (See Figures 3-5 and 3-6). These experiments indicated that our original lower discrimator settings were acceptable. (Scattering increases at lower gamma-ray energies.)

Final system calibration (if one can use that term) involved the study of a number of subjects with apparently normal lungs. Results of this study are discussed in the final chapter of this thesis.

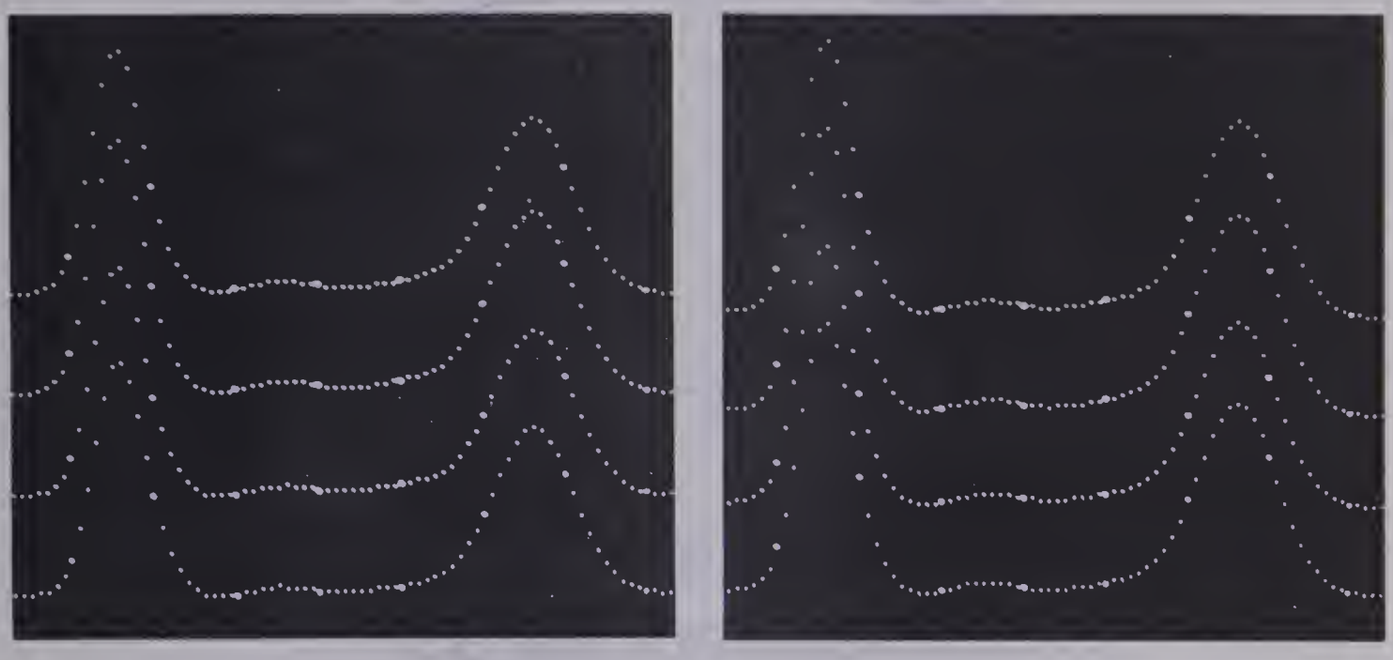


FIGURE 3-1

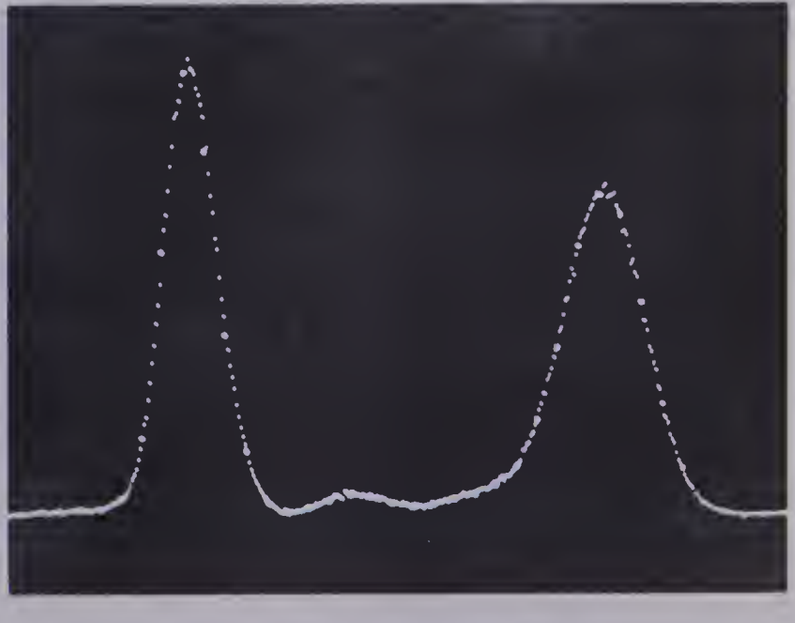
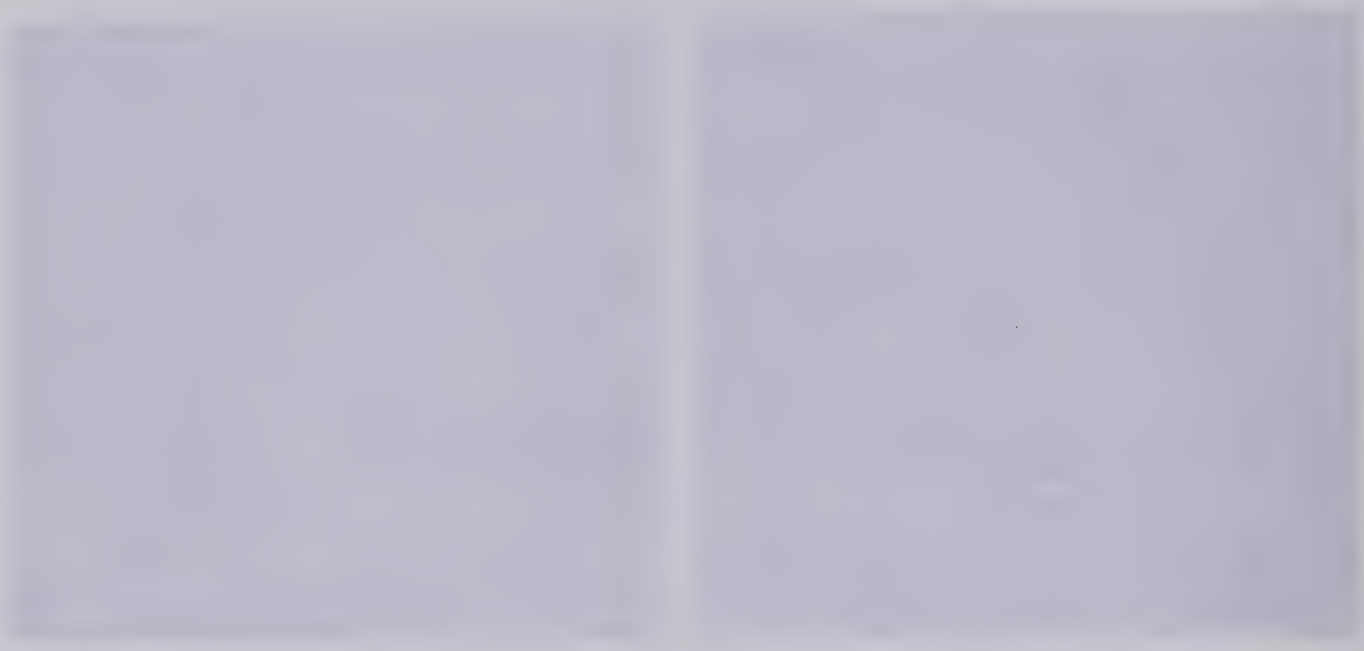


FIGURE 3-2



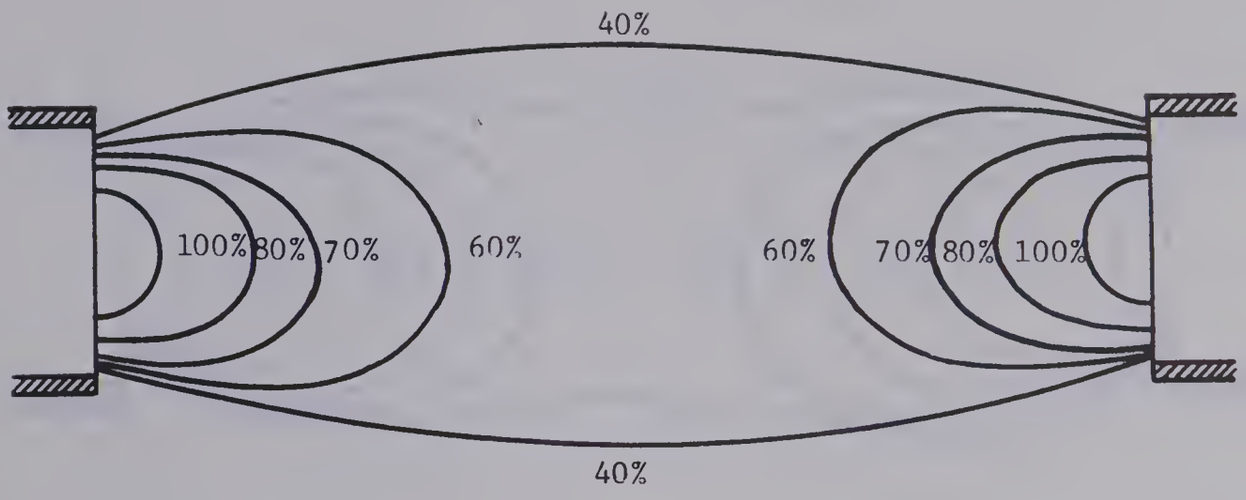


FIGURE 3-3

COLLIMATOR RESPONSE IN AIR

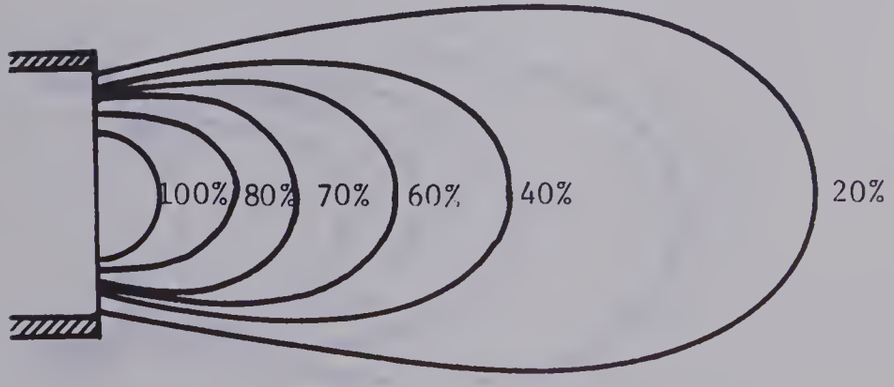


FIGURE 3-4

RESPONSE OF A SINGLE DETECTOR IN AIR

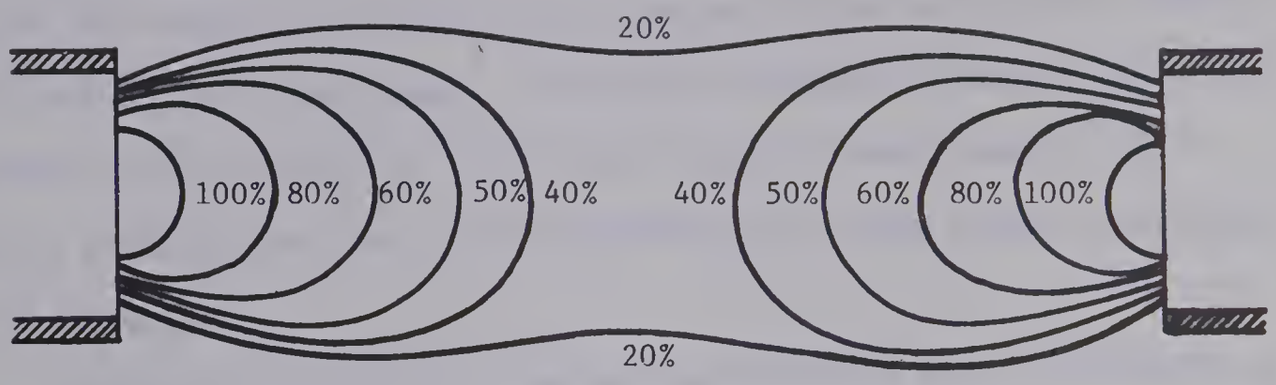


FIGURE 3-5
COLLIMATOR RESPONSE IN WATER

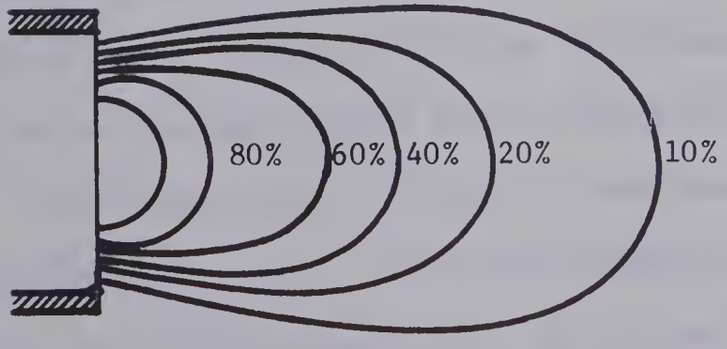


FIGURE 3-6
RESPONSE OF A SINGLE DETECTOR IN WATER

CHAPTER 4

TECHNIQUE

As mentioned in Chapter 2 data from the movement of Xenon gas within the lungs is collected over a period of time to produce a curve for each of the 8 lung zones. In order to evaluate pulmonary function, several tests are required. The basic routine investigated in this thesis involved four parts. The significance of each phase is explained in this chapter.

Throughout each phase of the regional function test, the subject is maintained in a comfortable, relaxed position. This helps to ensure a normal physiological state. Nearly all portions of the test are done without any requirement for abnormal physiological maneouvers. Since accurate detector positioning is important, a relaxed state aids in minimizing the movement of the subject.

In Chapter 2 the design of a small collimated light beam was mentioned and also its use in initial patient-detector positioning and in subsequent maintenance of this position. The beam of light is normally used to locate a spot at the top of the manubrium. A small pencil mark placed on the skin allows easy verification of position.

The initial part of the test provides a means for measuring regional pulmonary perfusion. As with all tests which involve radiospirometry, a level of background noise must be determined and later compensated for. In order to establish this background contribution, 30 seconds of data is collected as the initial part of each of 8 curves.

The actual data representing perfusion is obtained by injecting a radioactive tracer into a catheter[16] which has been inserted into a cubital vein. When the background determination has been completed, 1 millicurie of Xenon-133 dissolved in 1 millilitre of normal saline is injected, and the catheter is immediately flushed with 5 to 8 millilitres of non-radioactive saline (with the aid of a three-way valve). This helps to achieve a bolus of radioactive material, and as a result, the accuracy of measurement is better than could be obtained without the use of the catheter and flushing technique. During the injection and subsequent radioactive Xenon clearance, the patient breathes through the mouthpiece connected to the spirometer and his expired air is vented outside. This procedure avoids increasing the background radiation level of the room as well as lowering the radiation dose to those who are working in that area.

For the perfusion study, the time base is set at 2 seconds per sample. Therefore, a time sequence of data is obtained over a period of 400 seconds. Immediately after the bolus of Xenon reaches a normal set of lungs, most of it is transferred from the blood to the alveolar air. From this point in time the concentration of Xenon is slowly washed out of the lungs by normal respiration.

The next series of tests deal with ventilation and lung volume. A known concentration of Xenon is placed in the left bell of the spirometer which is set to operate in a closed circuit configuration. The patient is allowed to inspire one or two normal breaths of air tagged with Xenon.

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16 Venocath, 21 gauge bore, 11 1/2 inch length

The time base used for this test is 1/10 second which allows an accurate definition of each breath. This test is repeated with a single inspiration to total lung capacity.

After the single breath tests, the time base is reset to 2 seconds and the patient is allowed to breathe to equilibrium with oxygen being added and carbon dioxide removed to accommodate the requirements of respiration. The fourth data set is obtained by again allowing the patient to breathe room air and expire the Xenon through a hose which leads outside the room. The data which represents "breathing-to-equilibrium" is termed the "washin" data, and the final set of curves are called "washout" curves. The analysis of the data is described in a later chapter. During the equilibration (or washin) procedure it is desirable to measure the volume inspired with each breath as well as the total volume of inspired gases per minute of elapsed time. This is done with the aid of an on-line computer as described in Chapter 2.

The information collected from these tests is composed of radioisotope counting data obtained from four different tests. The first test measures perfusion and the remaining tests provide information on regional ventilation. The ventilation data is derived from several single breaths, an equilibration, and a washout procedure. This data is stored along with suitable identification on digital magnetic tape for subsequent computer-assisted evaluation.

CHAPTER 5

ANALYSIS OF DATA

The most common technique for analysis of radiospirometric data involves making a series of measurements on the graphs drawn by a chart recorder. One of the disadvantages of this method is the uncertainty present in each measurement. In addition to the cumulative error when computations involving several measurements are performed, mistakes due to incorrect readings are prevalent. To avoid these pitfalls a method for digital computer analysis was developed.

In addition to achieving greater accuracy and more reproducibility of results, the computer eliminates a great deal of laborious hand calculation which in itself is a source of many errors. Nevertheless, one must remember that many features of a data set which may be obvious to a human observer can be difficult to locate with a computer. Often this is because the eye can obtain a complete overview of a curve, whereas the computer must examine the data on a point-by-point basis. With this in mind it was necessary to derive algorithms which would overlook imperfections in the raw data but not miss the significant characteristics of the various curves.

This chapter describes the analysis performed on data which is obtained by the technique outlined in Chapter 4. Whenever there is doubt as to the validity of the computed results, graphs of the unprocessed data are examined for possible ambiguities and the results are interpreted accordingly.

Figures 5-2 to 5-5 show a typical set of curves obtained by the methods used for the basic test. Photographs of some curves taken from

an oscilloscope are shown in Figure 5-6. The curves obtained by injecting Xenon-133 intravenously will be discussed first. In order to establish a level of background radiation, data collection is started 30 seconds prior to the injection as outlined in Chapter 4. When the Xenon reaches the perfused areas of the lungs, most of it diffuses into the alveoli. This point is marked by a peak in the perfusion curves. As the gas is breathed out of the alveoli, the activity concentration in the lungs decreases (assumed exponentially) until all ventilated alveoli have been cleared of Xenon. Indices of perfusion are calculated from the relative heights of the 8 curves. (The response from one detector is shown in Figure 5-2.) These indices are then expressed as a percentage of total perfusion.

To measure ventilation of perfused lung area, the time at which the Xenon concentration reaches one half of its peak value is computed. A shorter time indicates better ventilation for that particular area of lung. To obtain actual ventilatory rate expressed as a percentage of total, the following calculations are performed:

$$\text{Regional clearance rate} = \frac{\text{volume}_i}{T\ 1/2}$$

$$\text{Mean clearance rate (MCR)} = \sum_{i=1}^{8} \left[\frac{\text{volume}_i}{(T\ 1/2)_i}\right]$$

$$\text{Ventilation per unit volume (V./V)} = \frac{1}{T\ 1/2} \div \text{MCR}$$

$$\text{Regional ventilation} = (V./V) \times V \times 100$$

Other factors calculated are perfusion/volume ratios (Q./V) and ventilation/perfusion ratios (V./Q.). The method of calculating these values is readily apparent.

A single inspired breath is used as another way of calculating ventilation. The maximum height of each curve is located, corrected for

background and used to obtain a measure of ventilation, computed as a percentage of total ventilation. Ventilation/volume (V./V) and ventilation/perfusion (V./Q.) ratios are obtained from the point of view of a single breath.

The equilibration, or washin, curve is used to obtain a measure of both volume and ventilation. After 30 seconds of background information, the patient is allowed to breathe from the spirometer containing Xenon-133 and the curves show a sudden increase in radiation due to the inspiration of Xenon. The slope of this part of the curve provides a measure of ventilation which, however, is dependent upon the breathing rate of the patient. To avoid this extra parameter, a mean clearance rate is again computed and used to normalize ventilation to a percentage of the total. The time required to reach one half of the equilibrium concentration is used to indicate ventilatory rate, as in the perfusion washout analysis. Once again the V./V and V./Q. ratios are calculated and included in the summary of results. The volume parameter which is used for normalization in all phases of the analysis is calculated from the relative equilibrium activity levels. The volume constants (K) are expressed as percentages of total lung volume.

The washout curves are obtained by once again allowing the patient to breathe room air. In this way, the concentration of Xenon in the lungs is decreased. However, because the lungs have held Xenon for several minutes, some of it has been carried by the bloodstream and deposited in fatty tissues in the chest wall and other parts of the body. Xenon in this compartment takes a little longer to wash out of the body because it must first be carried by the blood back to the lungs before it can be expired. This slow component of the washout curve

FIGURE 5-I

must be separated from the faster component in order to calculate ventilation. A two component curve peeling method is employed to obtain exponential representation for the washout data. Once the fast component has been found, the analysis proceeds in the same manner as for the washout portion of the perfusion curves.

Much work was necessary to properly define the two exponentials. In order to provide reproducible results, the definition of the slow compartment was limited to the final minute of the washout curves. In a practical sense, this simplified curve stripping technique was adequate for the purpose of this study.

The computer program for data analysis was written in Fortran IV to run on an IBM 360/67 computer. It has since been modified to run on a Hewlett-Packard 2116B computer which is also used for on-line tidal vol- volume monitoring. One of the reasons for using the small computer was the availability of immediate results. Processing of data on the large scale machine required several days for transfer of tapes and the return of printed output. In addition, the cost of using the large computer was considerably greater than that of the small laboratory machine.

Following is a description of the function of each subroutine in the data analysis package. For a listing of the complete program, see Appendix I.

I. MAIN

The main program functions primarily as an interactive link with the operator. Its functions include the following:

1. Input parameters - e.g. time base used, tagword identifier of data, type of curve to be analyzed, name of patient, etc.
2. Locate and read data from magnetic tape.

3. Set up initial tables which are required by the program.

4. Inform operator of any errors or abnormal conditions.

II. SMOOTH

This subroutine consists of two phases of curve smoothing. All data read from magnetic tape is examined by this routine. First, each of the 8 curves are scanned to locate obvious errors arising from faults in the data collection system. Anomalous data points are corrected and a total count of such replacements is kept for later printout. Next, a five point curve smoothing algorithm utilized. The name of this subroutine is SE15.

III. SE15

The routine employs a five point linear algorithm for reducing the statistical fluctuation caused by counting random events (i.e. disintegration of the radioisotope Xenon-133). This statistical variation is especially pronounced at the low counting rates encountered when collecting data from a single breath of inspired Xenon. However, even when the counting rate is higher, the smoothing technique helps to minimize the number of incorrect decisions due to individual points which deviate excessively from the mean. The smoothed curves are stored in memory for analysis by later routines.

IV. PERF.

This part of the program analyzes the perfusion curves to determine whether or not there exist peaks which are contributed by tissues other than the lungs. One reason for this is to eliminate the artefact introduced by the bolus of Xenon passing through the subclavian vein and the superior vena cava. Any false peaks which are found are printed out and the curve analysis part of the program notified of their existance.

V. EXTRCT.

The function of this routine is to extract the largest remaining element from a given data set. Each time it is called, the next largest element in the data set is extracted. Parameters passed from subroutine PERF cause EXTRACT to ignore false high points.

VI. SINGLE

This routine, together with several called subroutines, does the major portion of the actual curve analysis. A parameter from the MAIN program determines the type of analysis to be performed. For each type of curve except "washout" a background level is obtained and subtracted from the data to be analyzed. Other functions of this routine are dealt with according to curve type.

1. For perfusion the following tasks are performed: (See Figure 5-2)
   a) determine the position and magnitude of the maximum point on each curve.
   b) correct for background both before and after the bolus injection.
   c) use a fitted exponential curve to determine the time required for one half of the Xenon to be expired.
2. Each single breath requires the following analysis: (See Figure 5-3)
   a) determine the position and magnitude of the maximum point on each curve (using a different algorithm from that used on the perfusion curves). The peaks of single breath curves tend to be more poorly defined than those present in the perfusion curves.
   b) a correction for background level is again performed.

3. Analysis of "washin" data: (See Figure 5-4)

   a) Equilibrium values for each region are determined. This allows a comparative lung volume measurement to be made. Later in the summary of results, the volume measurement is used as a normalization parameter.

   b) The point in time at which each washin curve begins is located.

   c) The curves are corrected for background radiation.

   d) An exponential is fitted to the point data to determine the time required for the concentration of Xenon to reach 50% of its equilibrium value.

4. Analysis of "washout" data: (See Figure 5-5)

   a) The point in time at which each washout curve begins is located.

   b) Since a background level is difficult to measure for the washout curves, an alternate approach must be used. Studies indicate that the concentration of Xenon-133 slowly builds up in fat and other body tissues when the lungs are maintained at a relatively high level of concentration. This leads to a very slowly decaying component of the washout curve. An attempt to separate the two components of the washout curve is one of the tasks performed by the FIT subroutine.

   c) The fast component of the washout curve is used to calcualte the time required for one half of the Xenon to be expired from the lungs.

VII. FIT

This subroutine will fit a one or two component exponential curve through a given set of data points. This is accomplished by fitting a least squares regression line to the natural logarithms of the data points. A curve stripping technique is used to separate the slow and fast components.

The slow component is determined by using the data collected during the final minute of the "washout". Next, this slow component is subtracted from the original curve and only the fast remains. Hence, the total curve is represented as the sum of two exponentials. If the errors involved with multicompartment analysis become large, the routine recognizes this and prints a message indicative of this situation.

VIII. LSQ

The process of exponential curve fitting produces linearized point data which is accessed by this routine.

The two functions of this routine are:

a) to compute a linear regression (of the form $Y = Ax + B$) to a given set of data points using the method of least squares.

b) to calculate the correlation coefficient for the computed regression line.

IX. SUMM

A set of tables containing a neatly formatted summary of results is presented by this part of the program. This summary includes parameters which represent the interrelationships of all of the accumulated intermediate results.

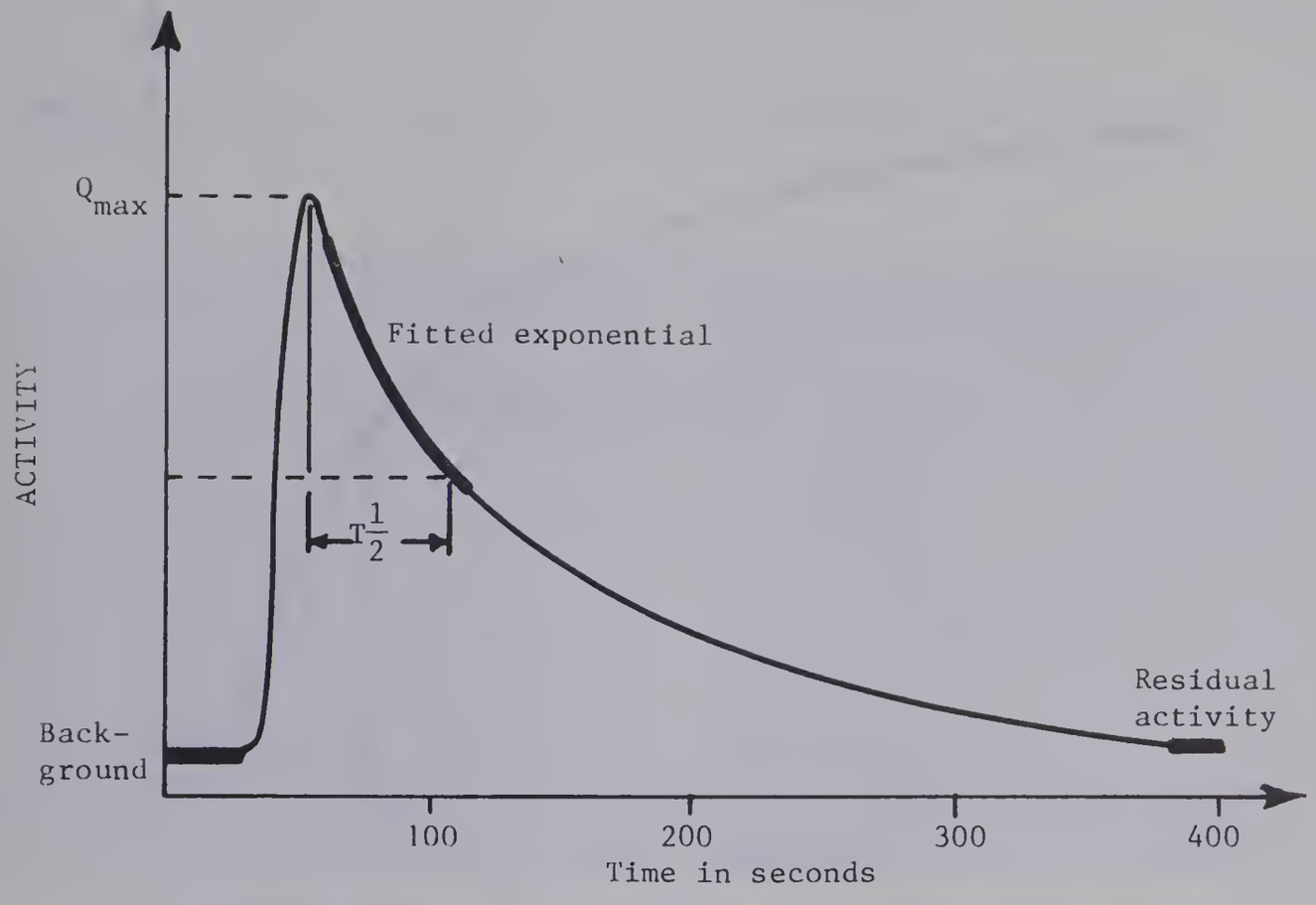


FIGURE 5-2 TYPICAL PERFUSION CURVE

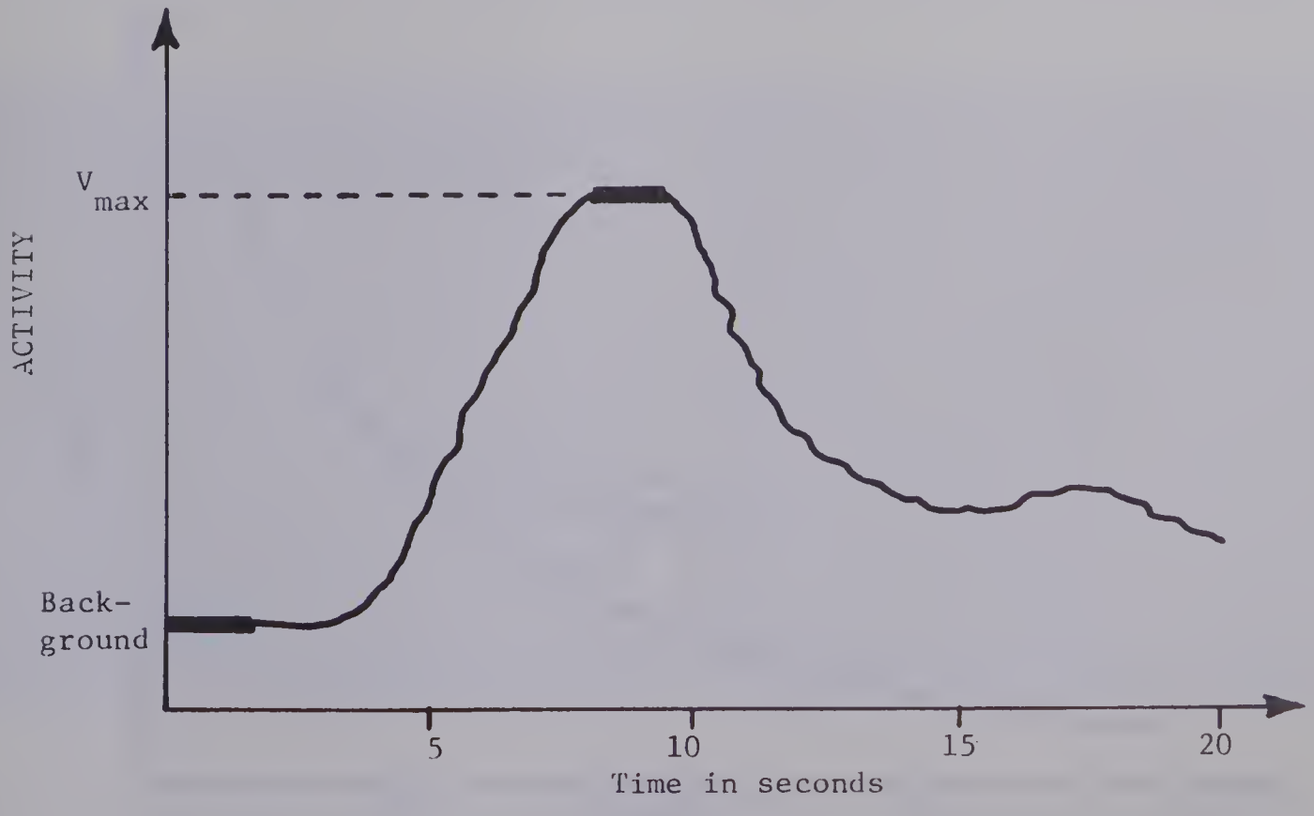


FIGURE 5-3 TYPICAL SINGLE BREATH CURVE

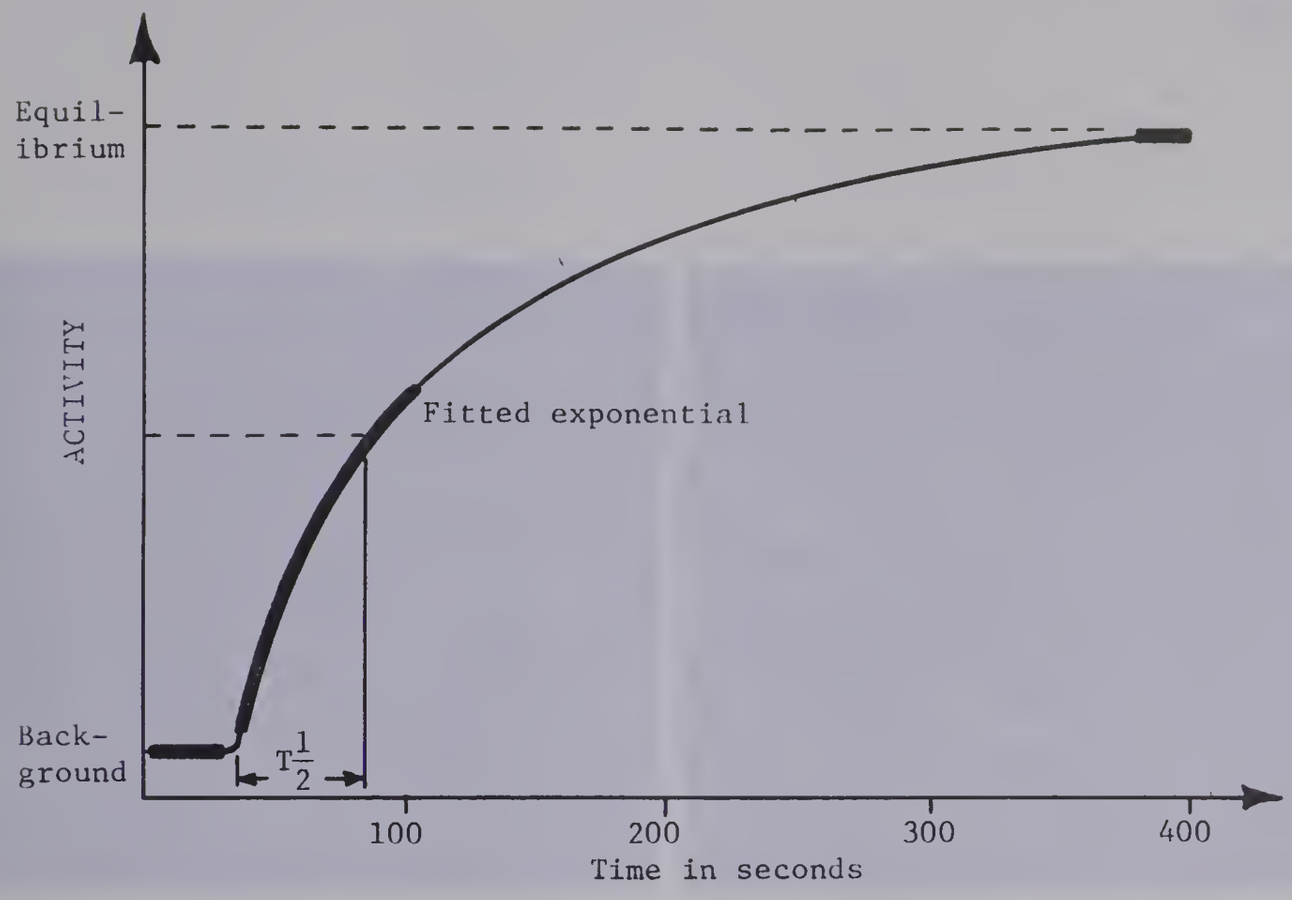


FIGURE 5-4 TYPICAL EQUILIBRATION CURVE

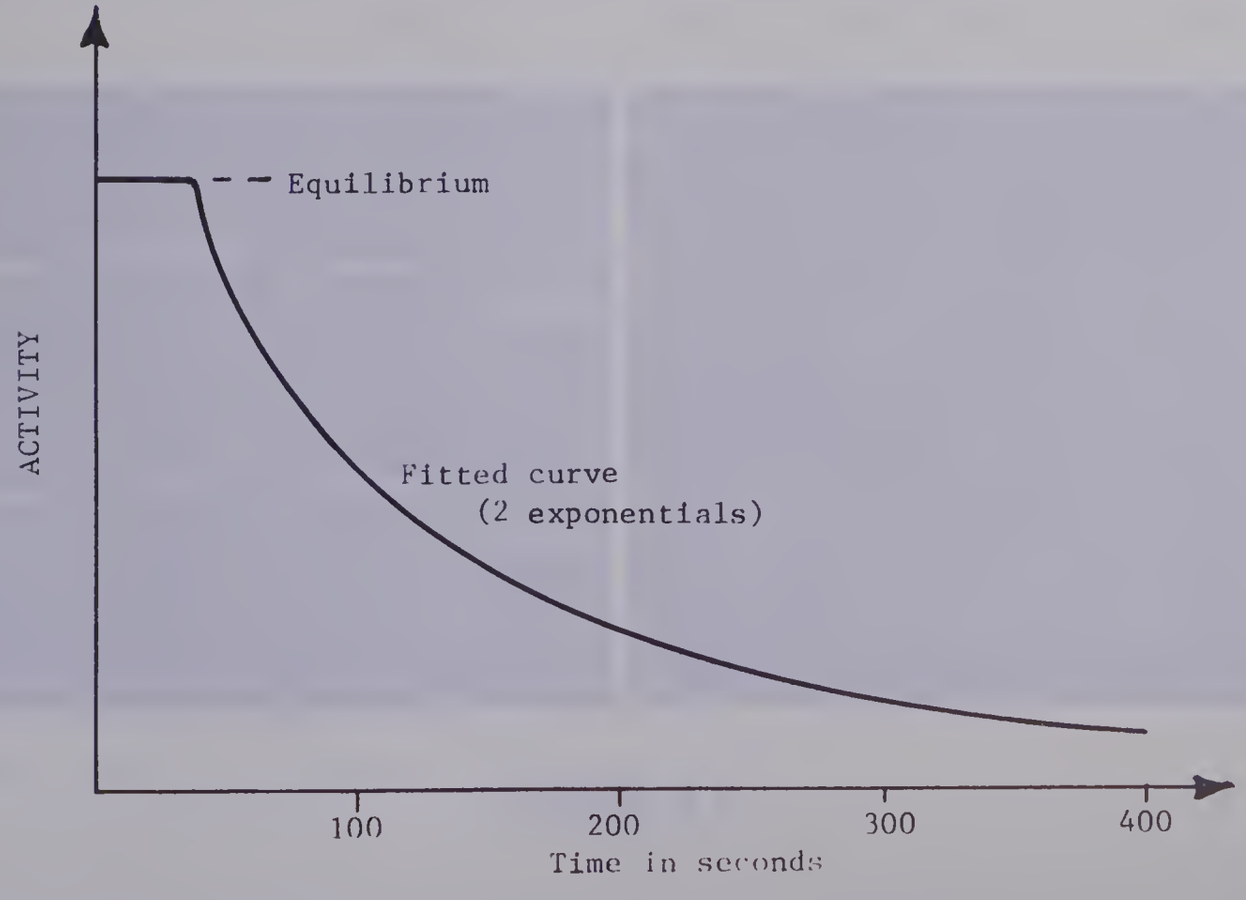


FIGURE 5-5 TYPICAL XENON WASHOUT CURVE

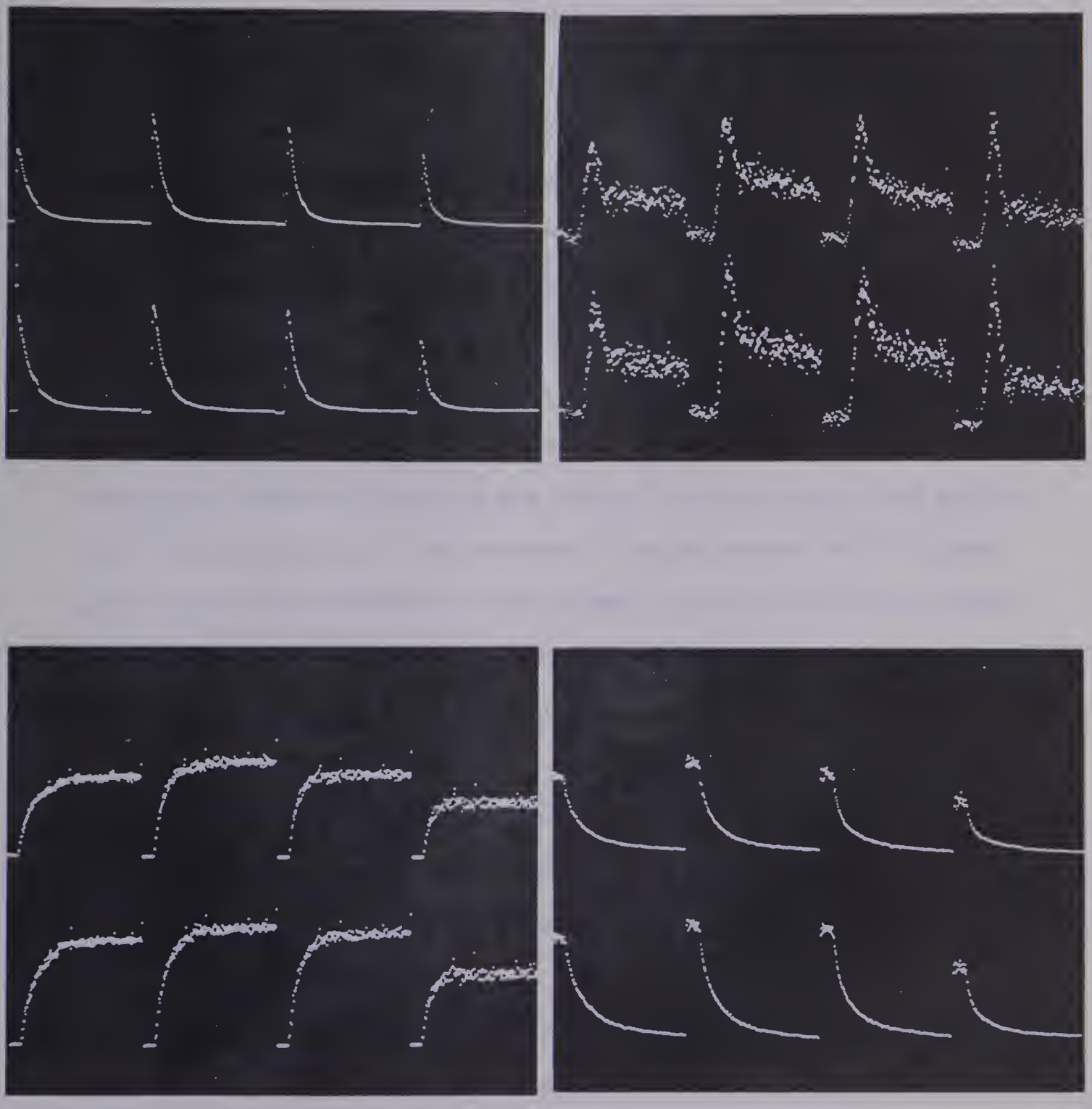


FIGURE 5-6

CHAPTER 6

MULTIPLE SINGLE BREATH TESTS

A. SINGLE BREATH TECHNIQUE

In addition to the previously described set of tests, one additional test of ventilation has been explored. This multiple single breath test has not been previously described in the literature and its concept is unique to our study. The general idea involved here is that of analyzing in detail each individual breath during a normal washin procedure.

A constant volume bag-in-box spirometer assembly is used so that the concentration of inspired Xenon will remain constant for each breath. (See Figure 6-3.) The Xenon gas is mixed with air in the box and spirometer circuit at the start of the test. The patient then breathes air tagged with Xenon-133 from the box through a one-way valve, and expires into the collapsed bag. The movement of the spirometer bell is again used to provide a measure of tidal volumes. At the end of each breath, the information collected in the memory is transferred automatically to magnetic tape. This procedure is normally done for a total of 20 breaths. Because the patient does not rebreathe, it is not necessary to add oxygen. A time base of 0.1 seconds is used for multiple single breath analysis. This allows a maximum breath length of 20 seconds. Figure 6-1 shows a typical set of curves obtained with breath #1 for each of the 8 lung areas.

Figure 6-2 shows a series of curves obtained by collecting data from one lung region for a period of several breaths. To find out how these curves are analyzed, turn to Section C.

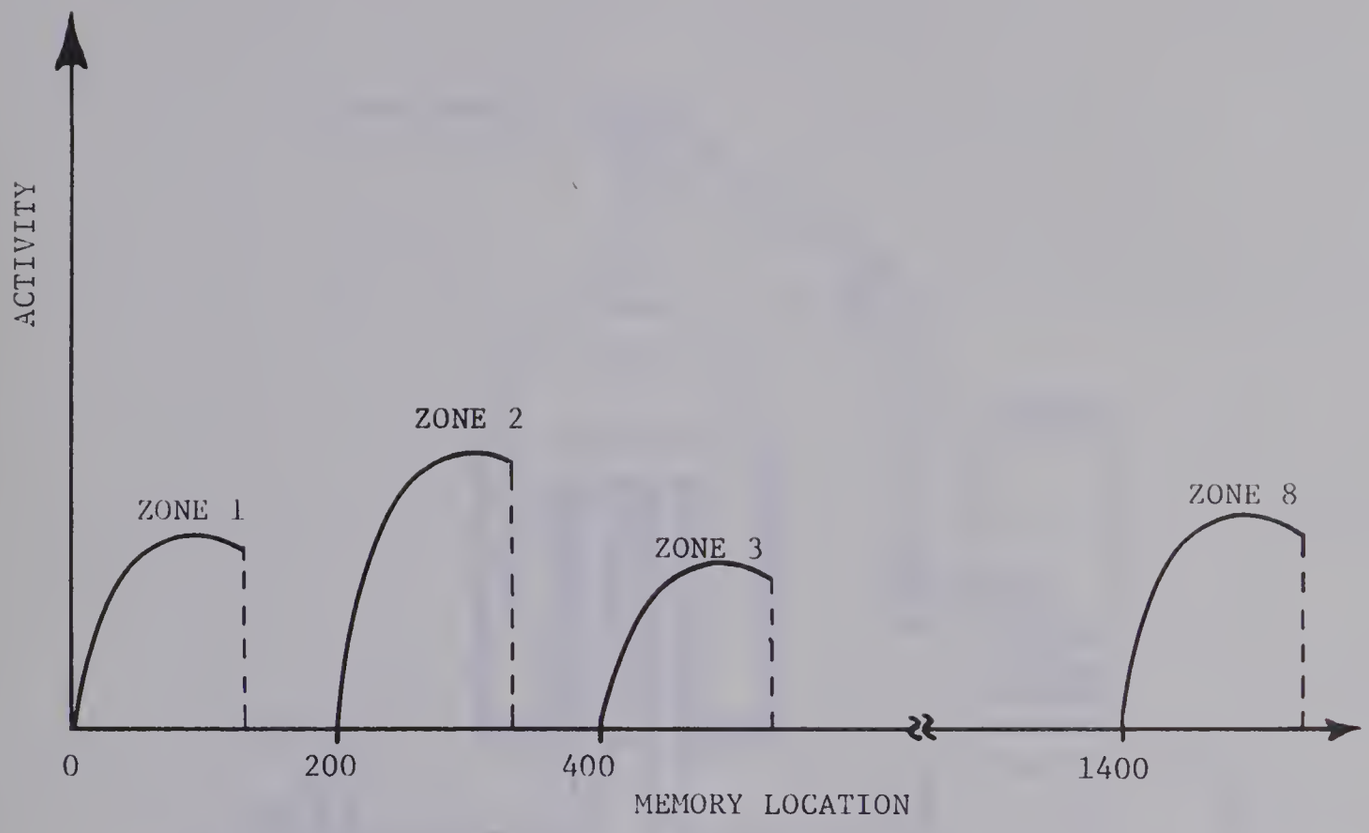


FIGURE 6-1 COLLECTION OF DATA FOR A SINGLE BREATH

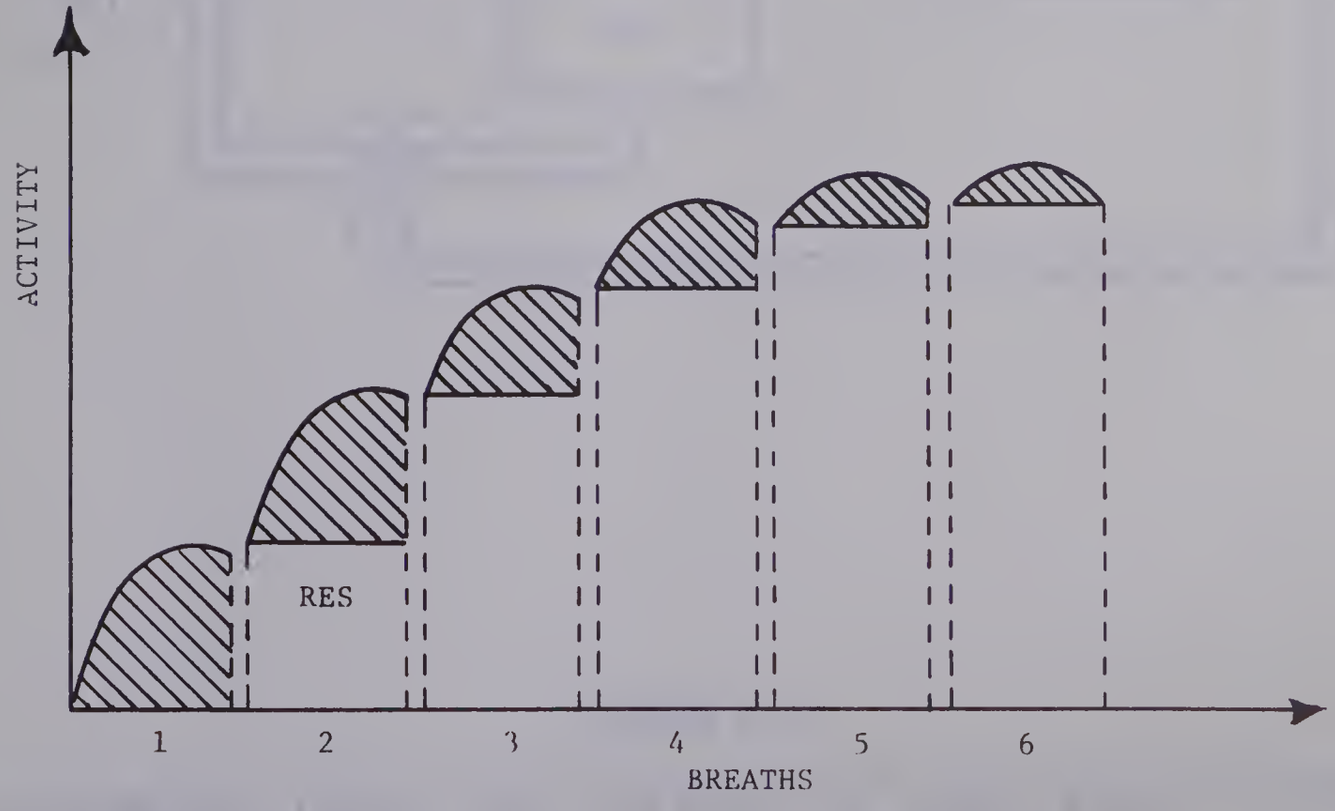


FIGURE 6-2 RESPONSE FROM SUCCESSIVE INDIVIDUAL BREATHS

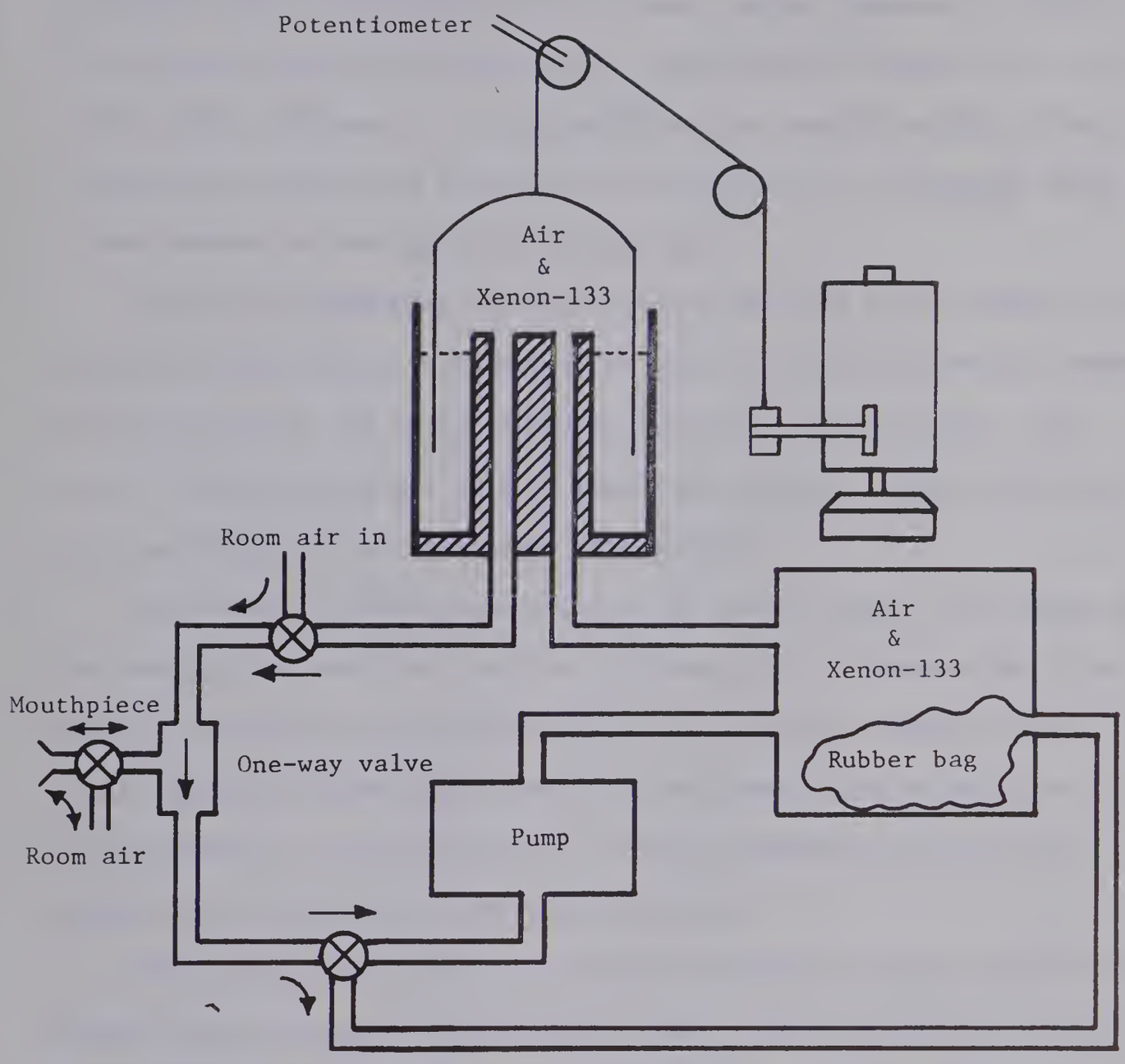


FIGURE 6-3

SPIROMETER CIRCUIT USED FOR MULTIPLE SINGLE BREATH STUDIES

B. THEORY OF OPERATION OF EOB SENSOR

The signal from the spirometer approximates a very low frequency sine wave with a considerable high frequency noise component. Before this signal reaches the pre-amplifier, the noise is filtered out and 150° phase delay is imposed. The pre-amplifier then amplifies this filtered fundamental waveform and removes the superimposed d.c. component which is always present at the input (See Figure 6-4).

The first differentiator stage obtains the sign of the slope of the amplified input signal. The output of this stage will be positive whenever the slope of the input signal is positive and vice versa. The output resembles a square wave of amplitude 20 volts. Zener diodes prevent saturation of the operational amplifier.

The second differentiator obtains the inverse sign of the slope of the rectangular wave from the first differentiator. Because the slope of the rectangular wave is zero most of the time, the output of this stage appears as a zero base line with positive and negative pulses corresponding to the inverse sign of second derivative of the input signal at the points where the slope is zero.

The fourth stage removes the negative pulses and shapes the positive pulses from the second differentiator stage. These pulses are used to trigger a monostable multivibrator which produces a 100 millisecond output pulse to the multiplexor. A second monostable multivibrator prevents a second output pulse from occurring before 1 second has elapsed. This is necessary in order to prevent a spurious signal from triggering the multiplexor before it has gone through a complete memory transfer cycle. Furthermore, complete breaths which are shorter than 1 second do not exist in normal tidal respiration. Erratic breathing, therefore, does not prematurely initiate a memory transfer cycle.

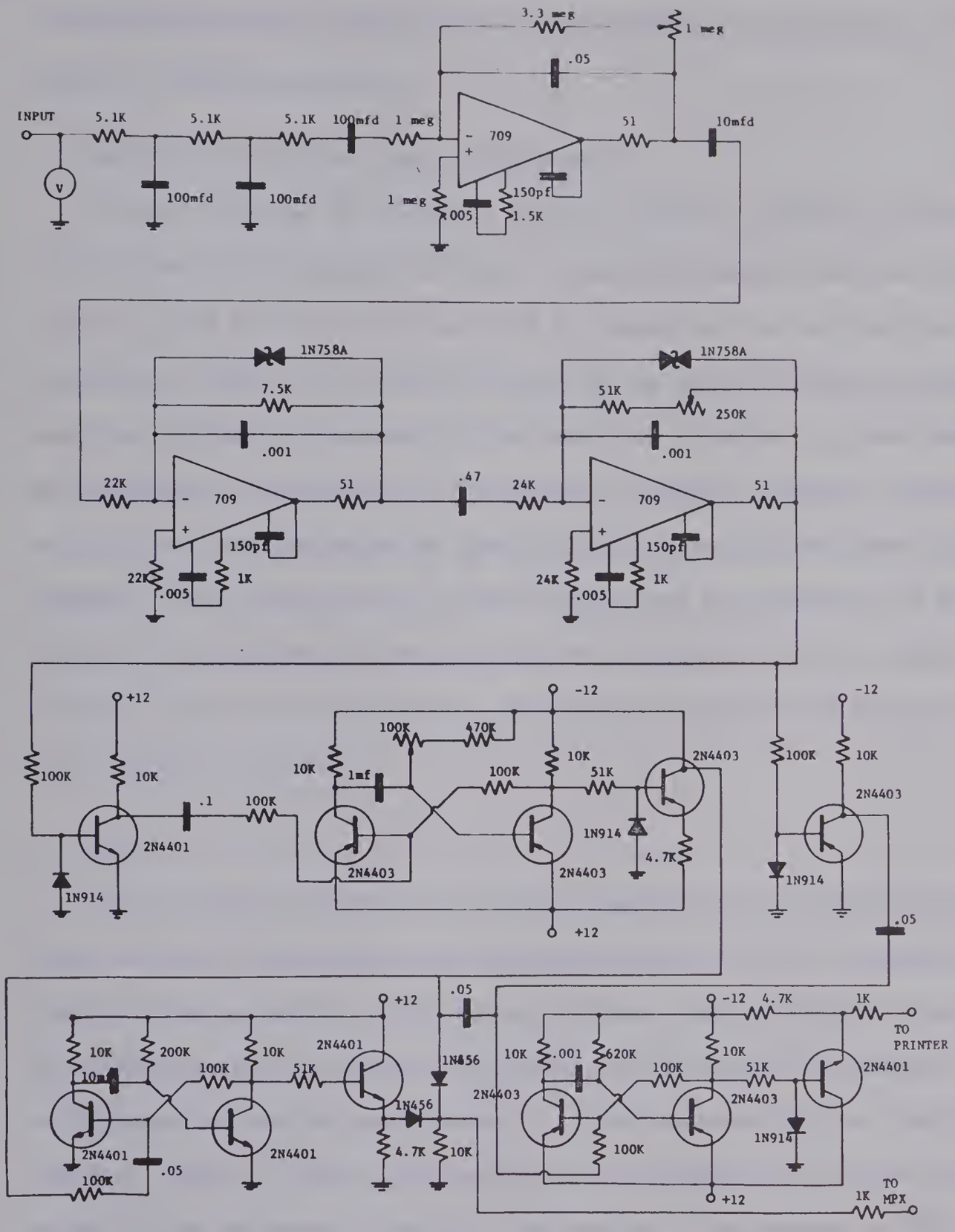


FIGURE 6-4

CIRCUIT DIAGRAM FOR END-OF-BREATH SENSOR

By using this device, it becomes possible to separate the data collected during each breath without interrupting the continuity of the subject's breathing pattern.

C. ANALYSIS OF MULTIPLE SINGLE BREATH DATA

As was indicated in Section A of this chapter, a number of consecutive breaths are collected, and their interrelationships analyzed and studied. This method is very new and its potential has not yet been fully determined. Much of the work done thus far is that of trying to supplement the information obtained by the basic set of tests. A great wealth of information is presented by the computer analysis program. However, the clinical interpretation of this information has not yet been fully explored. The algorithms can be best understood by examining the functions of the individual subroutines which constitute the data analysis package. All of the routines are written in Fortran IV and executed on an IBM 360/67 computer.

I. MAIN

The principal function of the main program is to initialize work areas and input the various parameters required later in the analysis. Some of these parameters include the patients name and date of test, the concentration of radioactivity used, the time base, and various calibration factors for each detector. Also required are the functional residual capacity (FRC) of the patient, and a measure of the dead space volume in the apparatus as well as the patient. Measurement of FRC is done with a standard helium dilution technique on the pulmotest and pulmo-analyzer. Dead space volume can be either measured independently or estimated. A listing of the parameters used is printed on the first page of each set of computer results.

II. TIDVOL

The tidal volume subroutine simply reads in the values for the tidal volumes and computes their average (TVA). In addition, the average of the first ten breaths (TV1) and the average of the breaths 11 to 20 (TV2) calculated. These averages together with the values of tidal volume are printed in a table.

III. DEAD

A correction for dead space volume is calculated for each breath according to the formula derived in Section D of this chapter. The corrected values of tidal volume which, incidently, are dependent upon the value of FRC, are included in the table of tidal volumes printed by the TIDVOL subroutine.

IV. INPUT

Many functions are performed by the INPUT subroutine. The obvious one is that of reading the data from magnetic tape. In addition, some preliminary data processing is done. The endpoint (NPT) of each breath is located and stored in memory. The data is normalized with respect to tidal volume, and residuals (RES) are calculated. To get an idea of what these terms mean, see Figures 6-1 and 6-2. The residual is then subtracted from each curve to leave only the data associated with the increment (INCR) for each breath.

V. SE15

This subroutine helps to reduce statistical fluctuations by smoothing the raw data before it is processed. A five point linear smoothing algorithm is employed.

VI. AVECUV

An examination of all data which has been read in from tape is performed in order to construct a set of 8 curves which represent an average breath. Three such averages are constructed. One is an overall average, one is an average of the first ten breaths, and the third represents breaths eleven to twenty. These three additional data sets are stored in memory for later analysis.

VII. ANACUV

The curve analysis subroutine determines the elementary attributes of each curve. These attributes include maximum height, rise time, plateau time, and duration of breath. Also the total area under the curve (INCR) and the area up to the maximum point on each curve (INCRM) is computed (See Figure 6-5). A table of these values is then printed.

VIII. INSIDE

In order to obtain a representation of the distribution of ventilation, the inside ratios are computed and printed. The ratios for each breath including the three average breaths are calculated on an individual basis. The ventilation is expressed as a percent of total and as a percent of the total for one lung. In addition, left-right ratios and percentages are calculated for each breath. All of these values are calculated three times. First the total integrals are used as a basis of measurement, next the integrals up to the maximum are used, and finally the relative maximum heights are used. These three representations for ventilation are printed together for easy comparison.

IX. OUTSIDE

To get an idea of the breath-to-breath variation of ventilation, another two ratio matrices are computed and printed. For each region of the lung, the ventilation measured on a particular breath is expressed as a percent of the average ventilation measured in that region. In this manner, the values in the table will exceed 100% whenever the ventilation is above average. Two outside ratio tables are printed. One uses integrals as being representative of ventilation and the other uses values of maximum curve height for comparison.

X. VENT

This routine uses the detector calibration factors and values of activity concentration to compute values for volume ventilation for each region of the lungs.

XI. LUNG

For convenience and clarity, a diagram of the lungs is printed. On this diagram, the position of each of the eight detectors is marked with a number corresponding to the number given to that area of lung elsewhere in the data analysis.

XII. POLFT

The next three subroutines deal with the computation of projected equilibration parameters. We assume the differences between successive residuals to approximate an exponential decay. Ultimately, after many breaths, differences between successive residuals will be very small and a state of equilibrium will have been reached. If a graph of the logarithms of the differences between successive residuals is plotted, it would appear as in Figure 6-6. The POLFT routine sets up a table of logarithmic values for each region of lung.

XIII. PLOTS

This routine organizes the data from the POLFT routine and calculates other parameters which will be used in the routine CORREL. Also, the projected 95% of equilibrium points are computed and printed in terms of the number of breaths required.

XIV. CORREL

Computation of maximum, minima, means, standard deviations, and correlation coefficients is performed for each region of lung. Linear regressions of the form $Y = A + Bx$ are computed and plotted together with a scatter graph of residual data points.

XV. PICT

As the name suggests, data is displayed graphically by this routine. Automatic 1-2-5 sealing is provided. One of the input parameters, GLOG, functions as a logical switch to determine whether or not graphs of all of the unprocessed data will be printed. Of GLOG is true, a graph containing data before and after smoothing is printed for each of the 8 regions associated with each breath.

XVI. FIXUP

This is a short routine which aids in generating statistical plots which arise out of data from the "CORREL" routine.

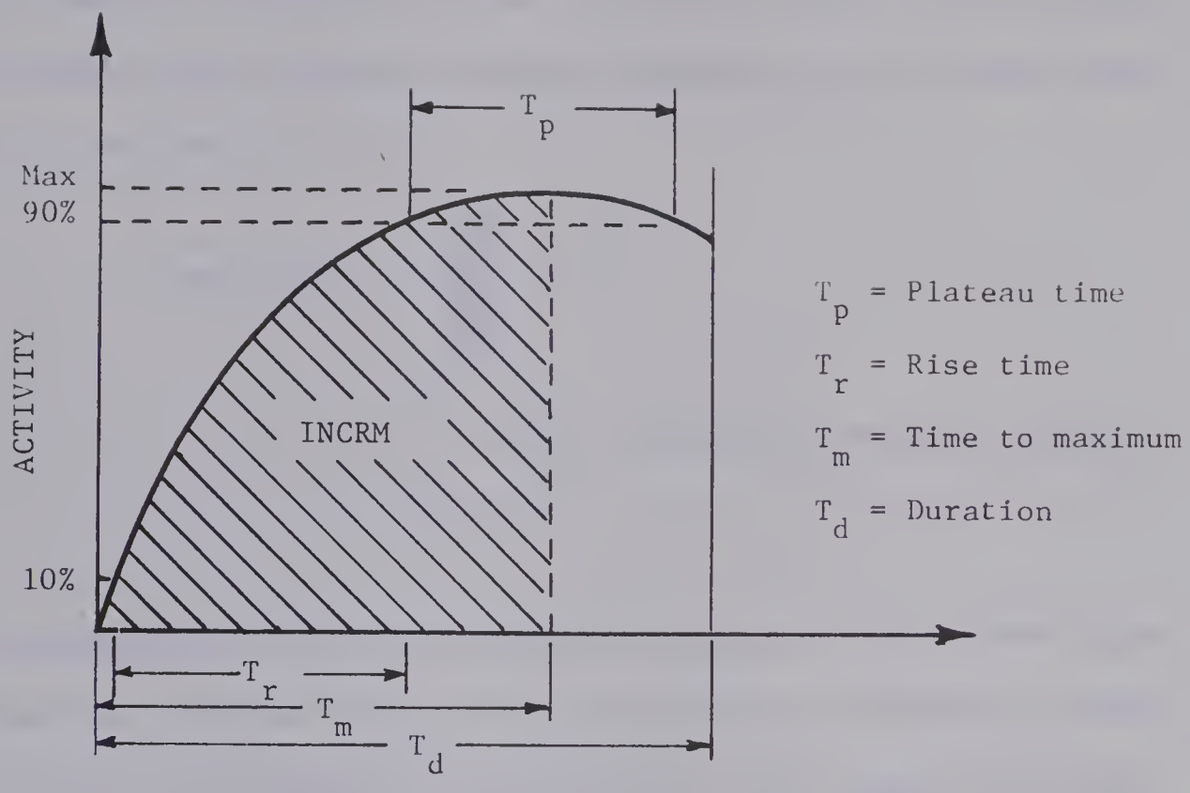


FIGURE 6-5

SINGLE BREATH CURVE PARAMETERS

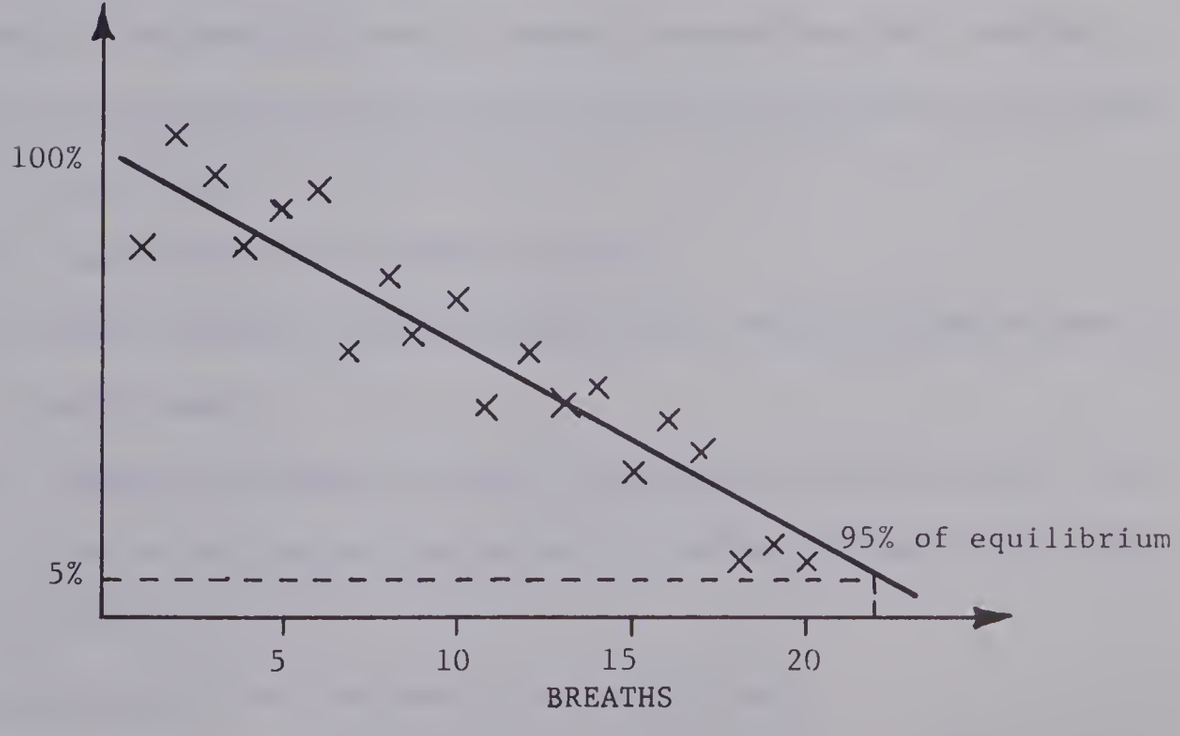
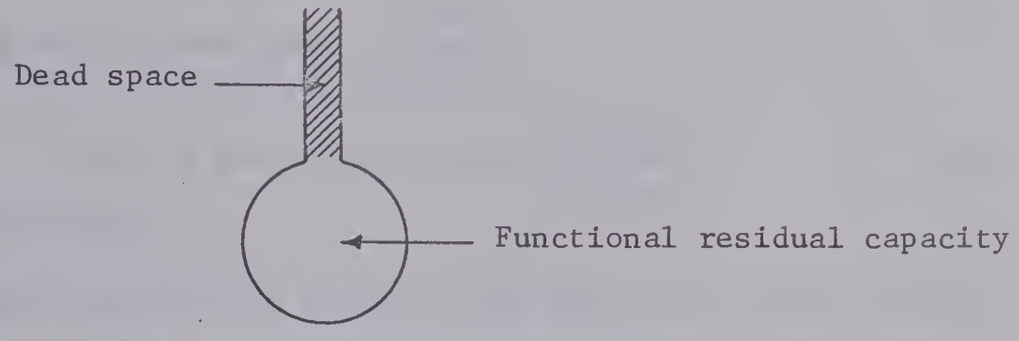


FIGURE 6-6

REGRESSION LINE FORMED BY EQUILIBRATION

D. CORRECTION FOR DEAD SPACE VOLUME

The lung can be assumed to be an inflatable balloon (corresponding to the alveoli) with a length of tubing (bronchial tubes) through which gases enter and leave.



The volume contained in the interconnecting tubing is termed dead space because gaseous exchange between blood and air is not possible in this region. When a person takes his first breath of air tagged with Xenon-133, only part of the breath actually mixes with the air already in the alveoli. The remainder never gets beyond the interconnecting passages. In deriving a mathematical model, several assumptions were required.

1) Dead space volume and FRC volume are distributed in the same proportion.
2) Dead space volume remains constant.
3) Perfect mixing of inspired gases and residual gases occurs with each breath.
4) Individual values of tidal volume do not include sighs. i.e. they do not deviate excessively from the average tidal volume.
5) $F >> V_T$.

The symbols used in the derivation are as follows:

V_T = tidal volume.

V_D = dead space volume (this includes both anatomical dead space as well as instrument dead space).

F = functional residual capacity.

V_{TVA} = average tidal volume.

Consider a situation at the end of one breath.

Amount of tagged gas inhaled = $V_{T1} - V_D$

Concentration in F and in dead space = $\frac{V_T - V_D}{F + V_{T1}}$

Amount remaining in F at the end of expiration = $\left[\frac{V_T - V_D}{F + V_{T1}}\right] F$ (1)

Consider the second breath.

The amount of inhaled activity is greater than that of the first breath because the dead space now contains some radioactive gas.

Amount inhaled from spirometer = $V_{T2} - V_D$ (2)

Amount inhaled from dead space = $V_D \left[\frac{V_{T1} - V_D}{F + V_{T1}}\right]$ (3)

The concentration now has 3 components arising from the combination of amounts (1), (2), and (3).

$$\text{Concentration} = \frac{V_{T2} - V_D}{F + V_{T2}} + \frac{V_D(V_{T1} - V_D)}{(F + V_{T1})(F + V_{T2})} + \frac{F(V_{T1} - V_D)}{(F + V_{T1})(F + V_{T2})}$$

$$\text{Amount remaining after expiration} = \frac{F(V_{T2} - V_D)}{F + V_{T2}} + \frac{F\ V_D(V_{T1} - V_D)}{(F = V_{T1})(F + V_{T2})} + \frac{F^2(V_{T1} - V_D)}{(F + V_{T1})(F + V_{T2})}$$

Now consider the third breath.

$$\text{Amount inhaled} = (V_{T3} - V_D) + \frac{V_D(V_{T2} - V_D)}{F + V_{T2}} + \frac{V_D{}^2(V_{T1} - V_D)}{(F + V_{T1})(F + V_{T2})} + \frac{V_D F(V_{T1} - V_D)}{(F + V_{T1})(F + V_{T2})}$$

$$\text{Concentration} = \frac{V_{T3}-V_D}{F+V_{T3}} + \frac{V_D(V_{T2}-V_D)}{(F+V_{T2})(F+V_{T3})} + \frac{V_{D2}(V_{T1}-V_D)}{(F+V_{T1})(F+V_{T2})(F+V_{T3})} +$$

$$\frac{F(V_{T2}-V_D)}{(F+V_{T2})(F+V_{T3})} + \frac{2FV_D(V_{T1}-V_D)}{(F+V_{T1})(F+V_{T2})(F+V_{T3})} +$$

$$\frac{F^2(V_{T1}-V_D)}{(F+V_{T1})(F+V_{T2})(F+V_{T3})}$$

At this point we substitute V_{TVA} for V_{T1}, V_{T2}, and V_{T3} in the denominator. This substitution will introduce little or no error if F, V_T, and all of the tidal volumes are not far from the average. This is usually true for relaxed normal breathing.

$$\text{Concentration} = \frac{V_{T3}-V_D}{F+V_{TVA}} + \frac{V_D(V_{T2}-V_D)}{(F+V_{TVA})^2} + \frac{V_D^2(V_{T1}-V_D)}{(F+V_{TVA})^3} + \frac{F(V_{T2}-V_D)}{(F+V_{TVA})^2} +$$

$$\frac{2FV_D(V_{T1}-V_D)}{(F+V_{TVA})^3} + \frac{F^2(V_{T1}-V_D)}{(F+V_{TVA})^3}$$

$$\text{Amount remaining} = \frac{F(V_{T3}-V_D)}{F+V_{TVA}} + \frac{(F^2+FV_D)(V_{T2}-V_D)}{(F+V_{TVA})^2} +$$

$$\frac{(V_D^2F+2F^2V_D+F^3)(V_{T1}-V_D)}{(F+V_{TVA})^3}$$

Finally, consider the fourth breath.

$$\text{Amount inhaled} = (V_{T4}-V_D) + \frac{V_D(V_{T3}-V_D)}{F+V_{TVA}} + \frac{V_D^2(V_{T2}-V_D)}{(F+V_{TVA})^2} +$$

$$\frac{V_D^3(V_{T1}-V_D)}{(F+V_{TVA})^3} + \frac{V_DF(V_{T2}-V_D)}{(F+V_{TVA})^2} + \frac{2FV_D^2(V_{T1}-V_D)}{(F+V_{TVA})^3} +$$

$$\frac{V_D F^2 (V_{T1}-V_D)}{(F+V_{TVA})^3} + \frac{F V_D (V_{T3}-V_D)}{F+V_{TVA}} + \frac{(F^2 V_D + F^3)(V_{T2}-V_D)}{(F+V_{TVA})^2}$$

Let us simplify the above expression by again substituting V_{TVA} for terms obtained from previous breaths.

$$\text{Amount inhaled} = (V_{T4}-V_D) + V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right]\left[1 + \frac{V_D+F}{F+V_{TVA}} + \left(\frac{V_D+F}{F+V_{TVA}}\right)^2\right]$$

If we stop the series at this point and examine the amount inhaled with the first four breaths we can see a trend developing. Instead of writing "amount inhaled", substitute "V_C" (corrected tidal volume).

$$V_{C1} = V_{T1}-V_D$$

$$V_{C2} = (V_{T2}-V_D)+V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right]$$

$$V_{C3} = (V_{T3}-V_D)+V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right]\left[\frac{1+V_D+F}{F+V_{TVA}}\right]$$

$$V_{C4} = (V_{T4}-V_D) + V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right]\left[\frac{1+V_D+F}{F+V_{TVA}} + \left(\frac{V_D+F}{F+V_{TVA}}\right)^2\right]$$

Generalizing we obtain:

$$V_{C1} = V_{T1}-V_D$$

$$V_{CN} = (V_{TN}-V_D) + V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right]\sum_{K=0}^{N-2}\left[\frac{F+V_D}{F+V_{TVA}}\right]^K$$

FOR N = 2, 3, 4,....

By examining this series we can see that if $V_{TN} \leq V_D$ no inhaled gas will reach the alveoli. This is also intuitively obvious. Also, for N very

large, $V_{CN} = V_{TN}$. To demonstrate this, use a binomial series:

$$(1-x)^{-1} = 1 + x + x^2 + \ldots. \text{ where } x = \frac{F+V_D}{F+V_{TVA}}$$

FOR N very large:

$$V_{CN} = (V_{TN}-V_D) + V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right] \left[\frac{1}{1 - \frac{F+V_D}{F+V_T}}\right]$$

$$= (V_{TN}-V_D) + V_D \left[\frac{V_{TVA}-V_D}{F+V_{TVA}}\right] \left[\frac{F+V_{TVA}}{V_{TVA}-V_D}\right]$$

$$= (V_{TN}-V_D) + V_D$$

$$= V_{TN}$$

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Considerable laboratory research has been required to develop the present technique of Xenon-133 radiospirometry. During the refinement of the procedures involved, a large number of volunteer normal subjects have been studied. To familiarize both the medical and engineering personnel with the capabilities of Xenon spirometry, a great deal of data was collected using a variety of clinical techniques. The procedures were modified several times before the present technique was adopted.

More than 100 subjects have taken part in the developmental stages of the research. However, due to the variation in the techniques and methods of storing and analyzing the data, only the more recent information proved sufficiently accurate to use for a general evaluation of the technique.

The graphs in Figures 7-1 to 7-4 show the mean values of the results obtained from 7 young female subjects. Regional lung volume, ventilation, perfusion, and ventilation-perfusion ratios are shown. The standard deviation associated with each point on the graphs is also shown. Figures 7-5 to 7-8 show a similar set of results obtained from 8 young male subjects. Neither of these groups of volunteers had any known lung diseases. The overall means and standard deviations for the group of 15 normals are shown in Figures 7-9 to 7-12.

An example of the results obtained from a subject with known lung disease is shown in Figures 7-13 to 7-16. This man suffered from chronic bronchitis and emphysema, and the distributions of volume, ventilation, and perfusion show a marked deviation from the normal trends.

The advantages of using the technique developed in this thesis are several in number. Since normal physiological conditions are maintained, the results are more meaningful than those obtained by breath holding or other forced respiratory maneouvres. Additional information can be obtained by repeating the study in a variety of positions as provided by the patient detector support assembly. The use of both front and rear detectors provided a more accurate definition of each zone of lung tissue. Errors due to analog devices and human intervention are eliminated by the digital data acquisition and analysis. Nevertheless it is important to consider future improvements.

Suggestions for Continued Research

Lung volume measurement necessitates accurate positioning of the subject. Very large and very small chests yield slightly different volume distributions. In order to better accommodate subjects who are significantly different from the normal, a change in detector arrangement is indicated. It is proposed to mount the detector-collimator assemblies on a subframe which will allow left-right spacing to be adjusted to suit the individual under study. The present assemblies maintain a fixed detector spacing for all tests. For this reason, the present system is not well suited to the study of children. All subjects studied thus far have been adults. Because the vertical spacing of the detectors is presently limited by the size of the photomultiplier tubes and collimators, this parameter cannot be conveniently changed. Hence, for small children, each lung could be divided into three areas instead of the four regions presently used for adults.

Much work remains to be done with multi-detector Xenon pulmonary studies. A detailed study of the effect of using only ventral detectors or only dorsal detectors would be useful. Some work has been done in this field by Aulin, et al[17].

Additional studies might include the effect of changing the degree of collimation and the effect of alternate detector positions. Further research in the development multiple single breath technique should prove very valuable. The measurement of cardiac output using another detector positioned directly over the heart may be helpful in determing absolute values of regional pulmonary perfusion.

Work is presently underway to develop a computer interpretation of the results obtained by the present technique. The computer would then compare the results with predicted values and arrive at a diagnosis and perhaps an indication of severity and location of the disease. In general, the advantages of a machine oriented diagnostic system cannot be taken lightly. The necessary pathways are open. The only requirements are confidence in the technique and more man-hours for development.

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17 Aulin, I., Lilja, B., Lindell, S.E., and Miorner in Malmo, Sweden

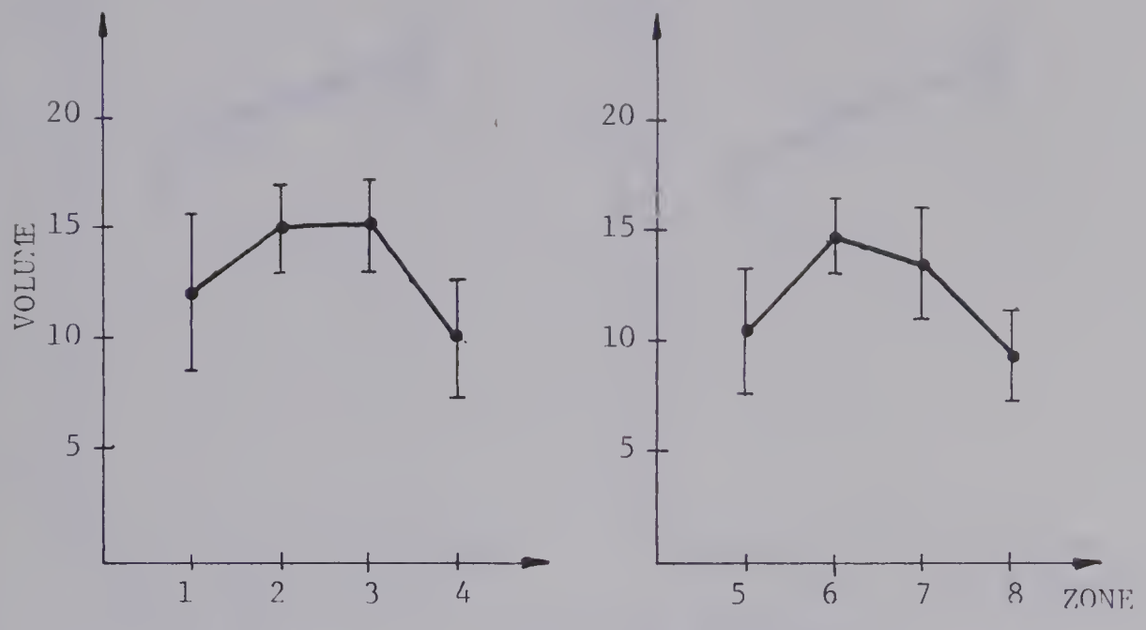

FIGURE 7-1 NORMAL FEMALES

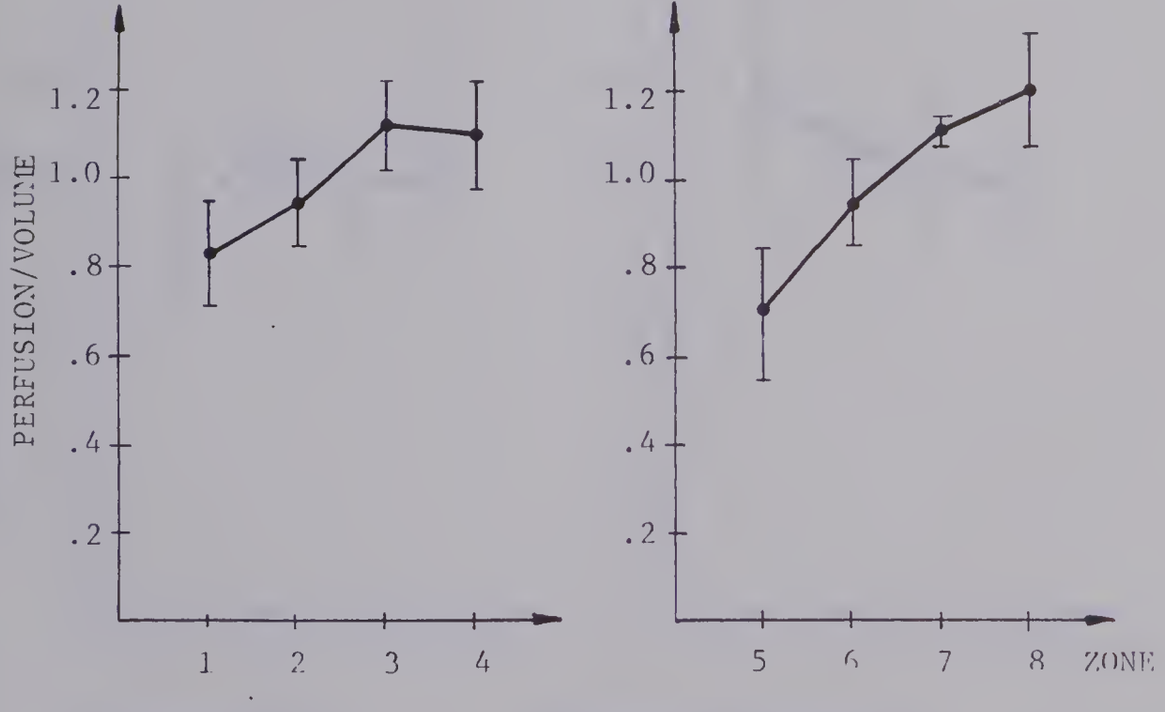

FIGURE 7-2 NORMAL FEMALES

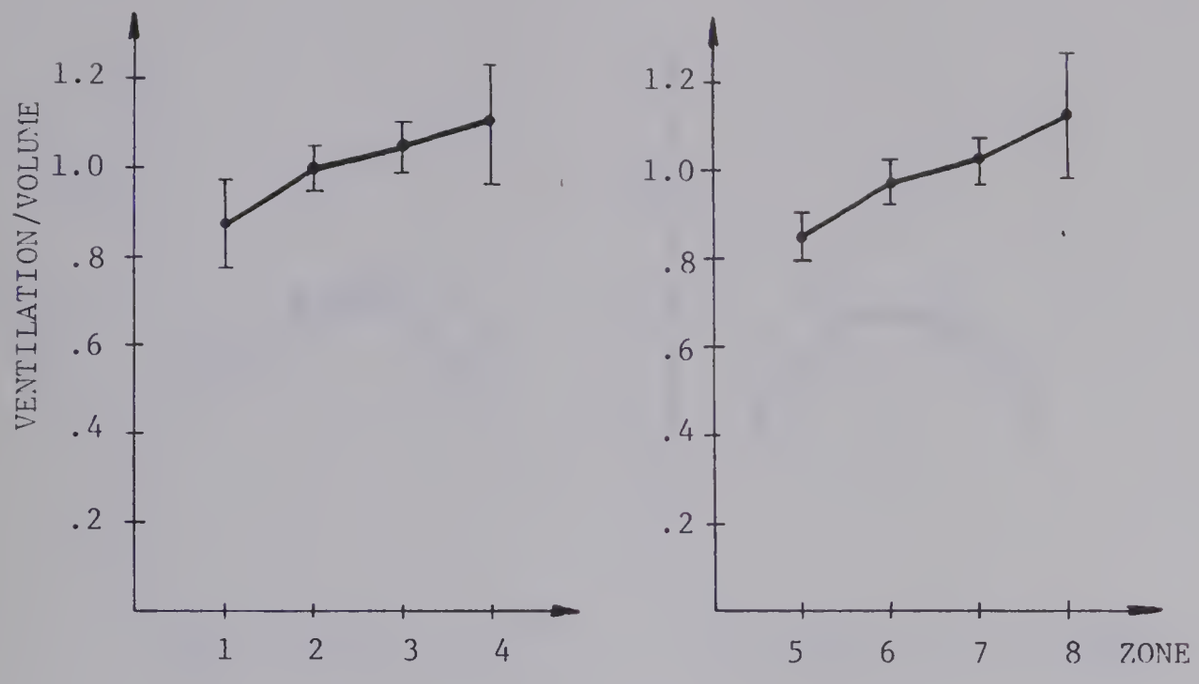

FIGURE 7-3 NORMAL FEMALES

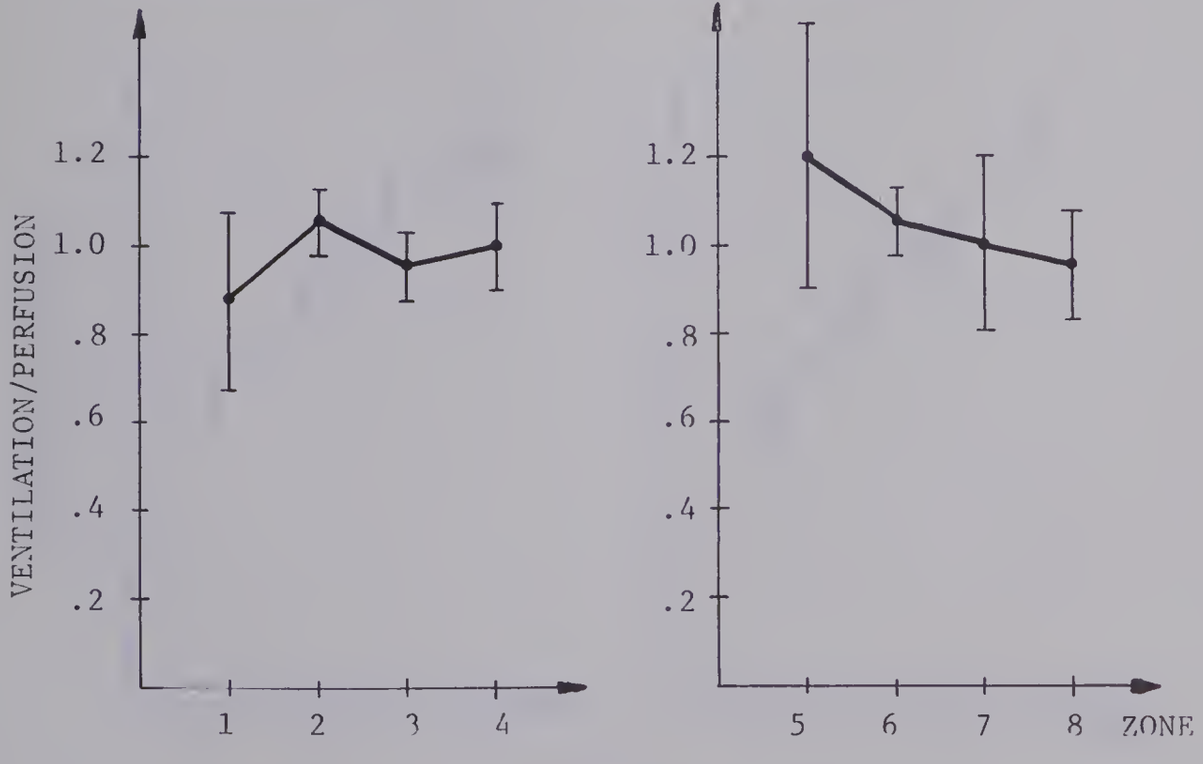

FIGURE 7-4 NORMAL FEMALES

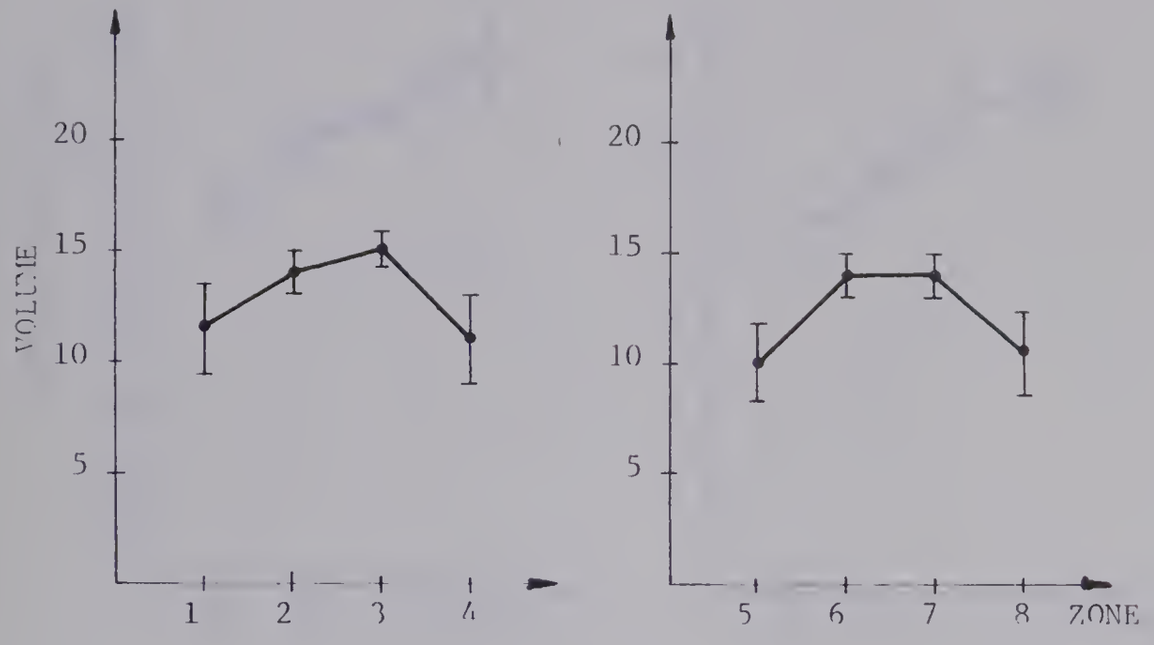

FIGURE 7-5 NORMAL MALES

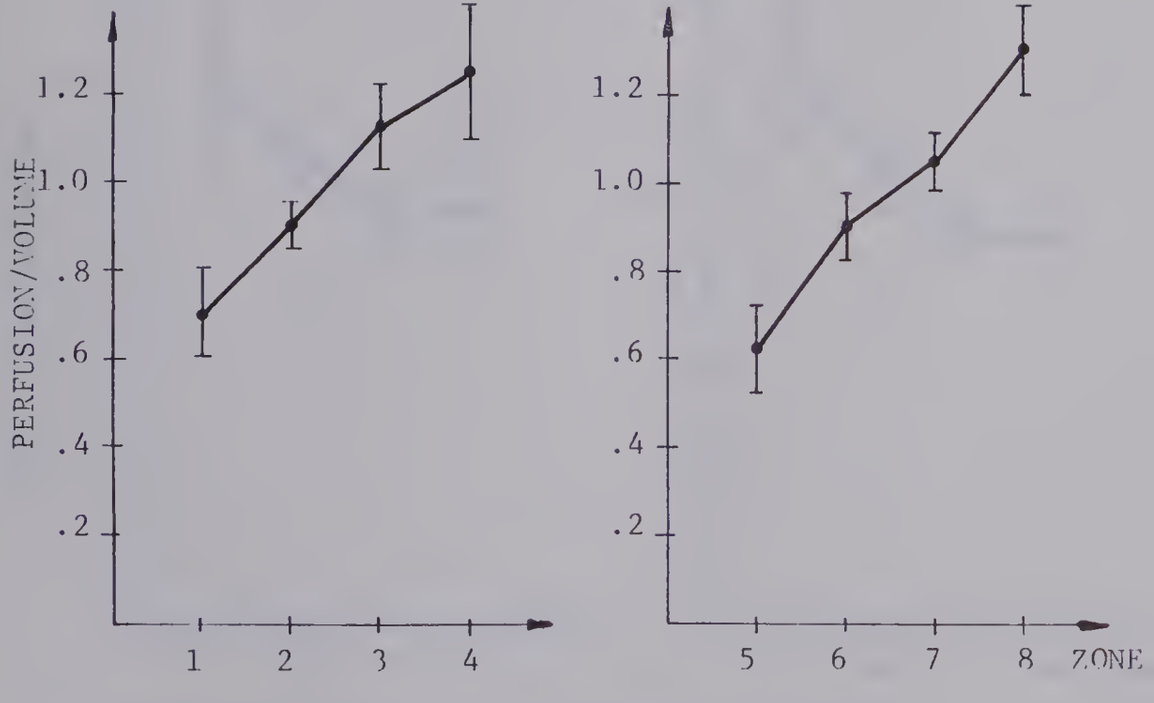

FIGURE 7-6 NORMAL MALES

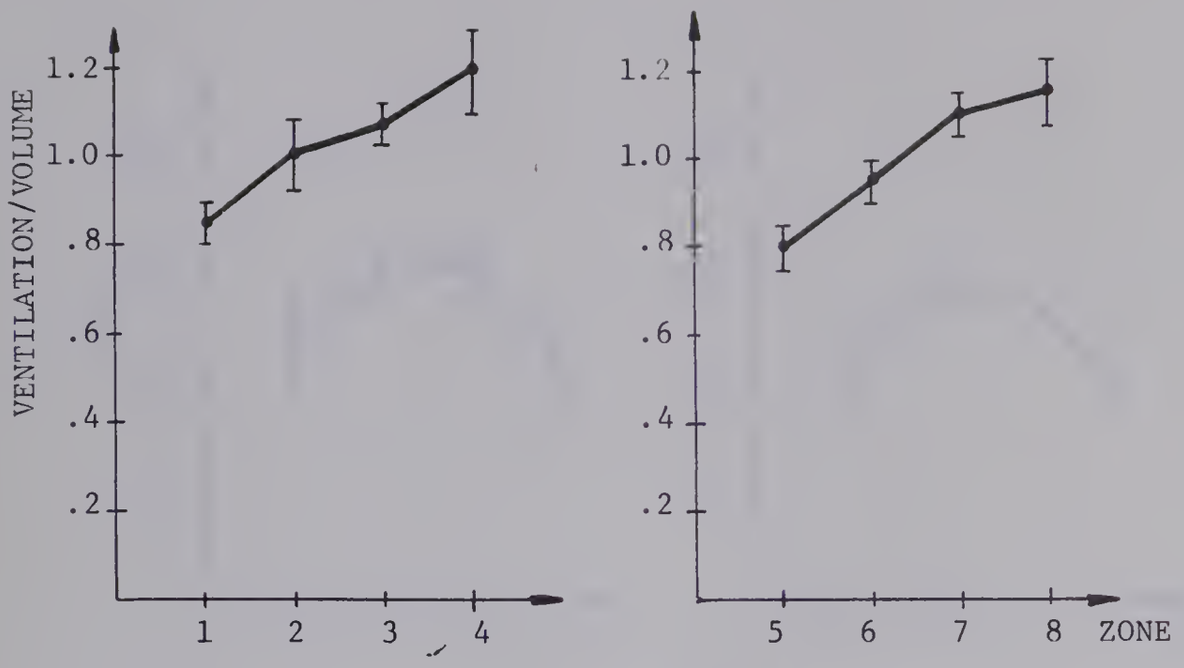

FIGURE 7-7 NORMAL MALES

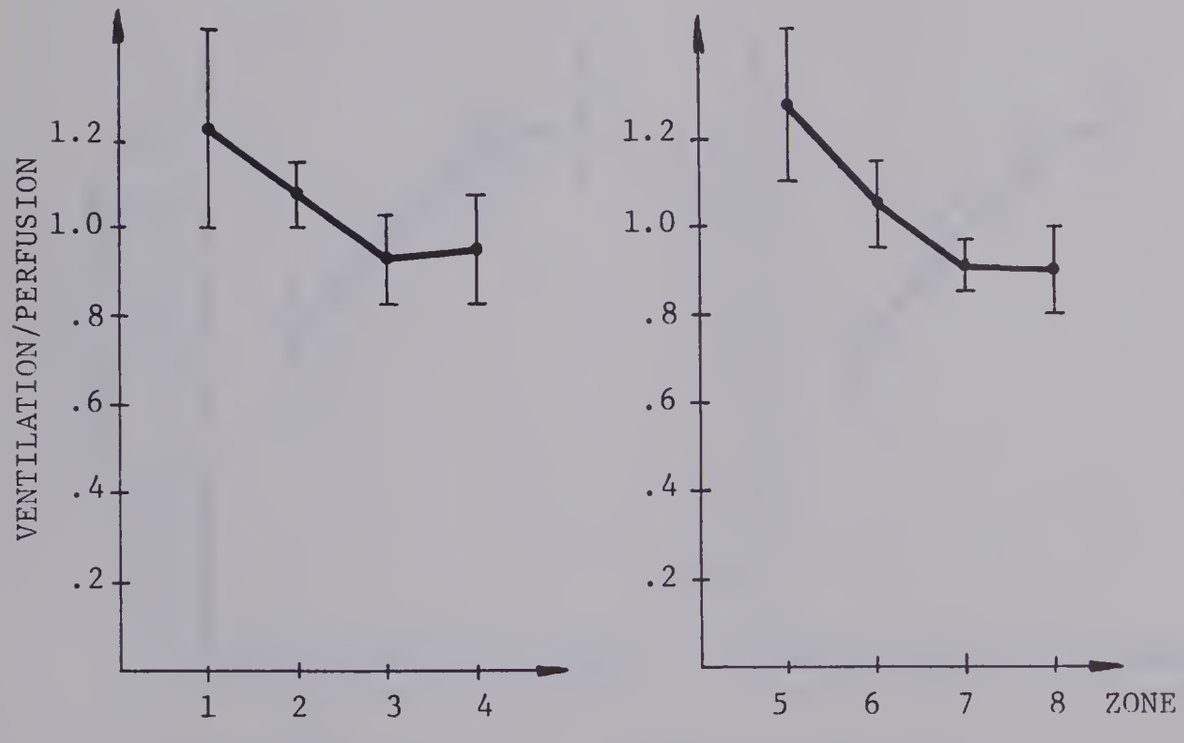

FIGURE 7-8 NORMAL MALES

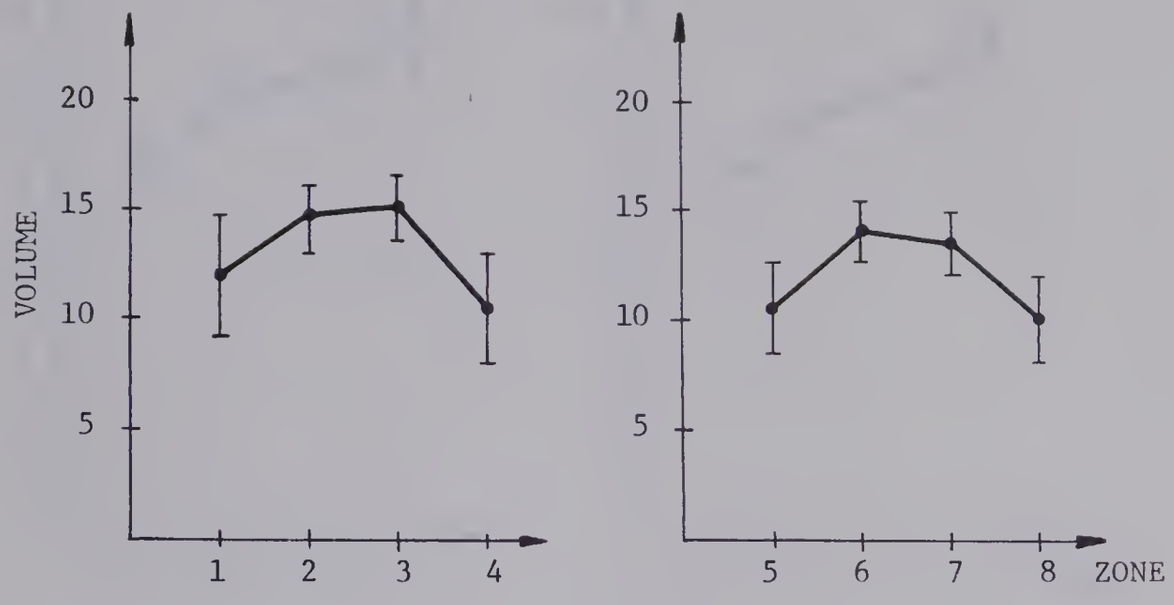

FIGURE 7-9 MALES & FEMALES

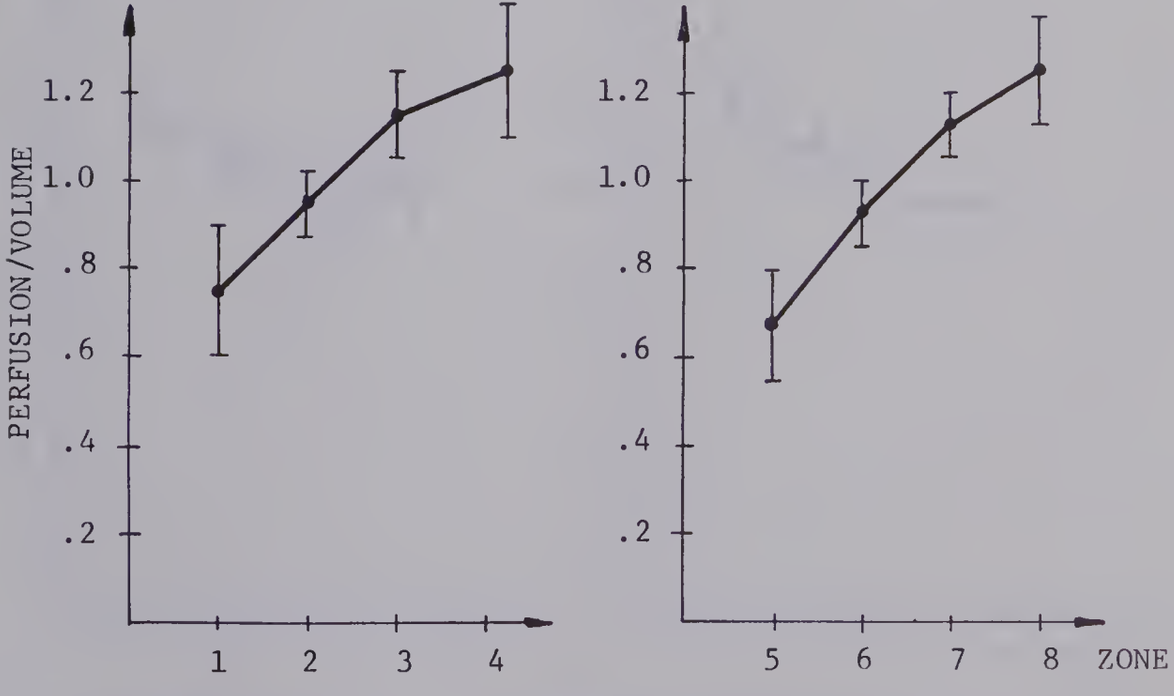

FIGURE 7-10 MALES & FEMALES

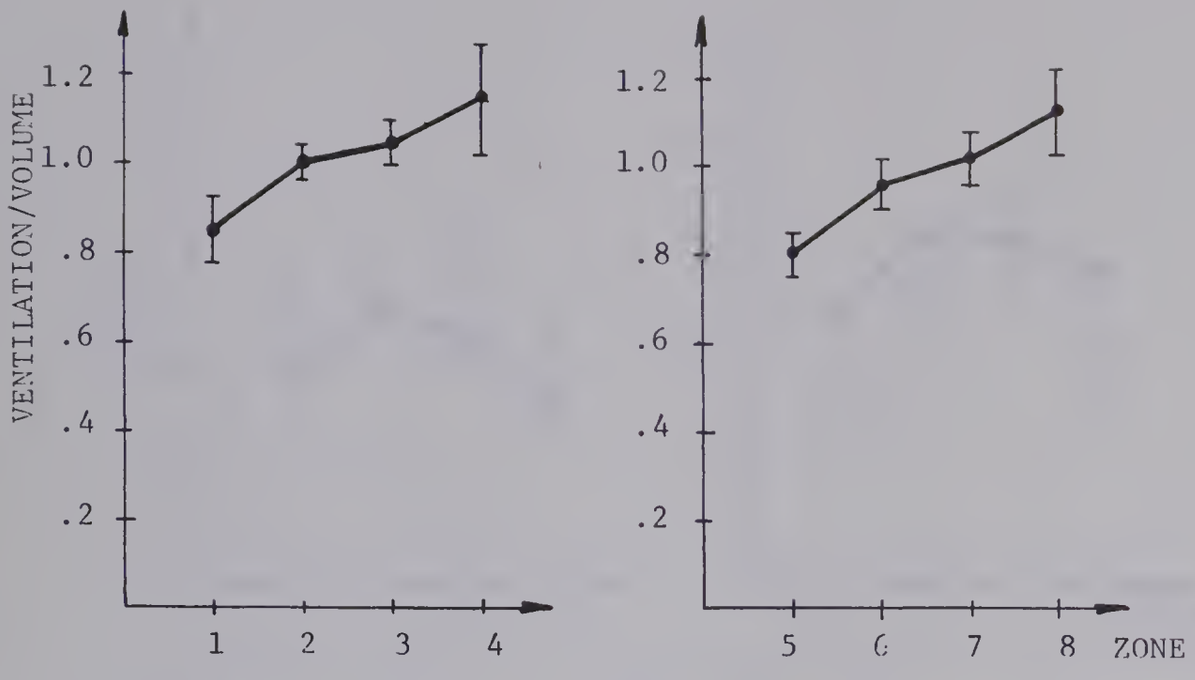

FIGURE 7-11 MALES & FEMALES

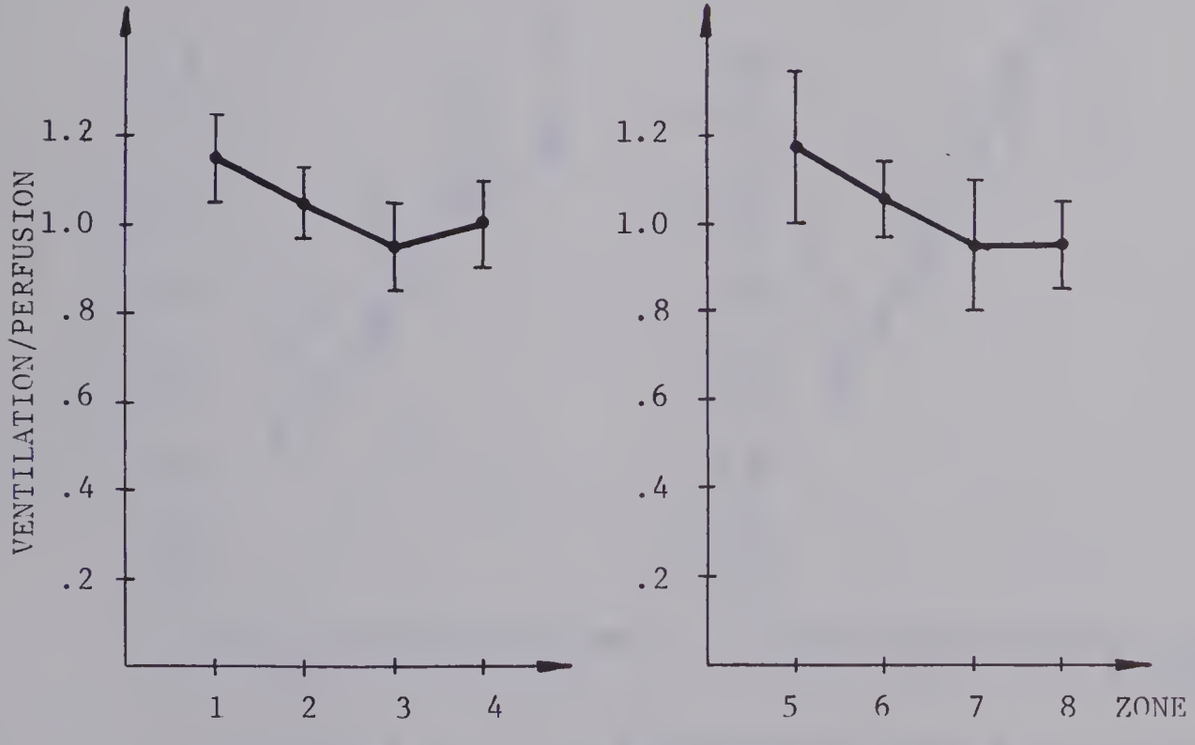

FIGURE 7-12 MALES & FEMALES

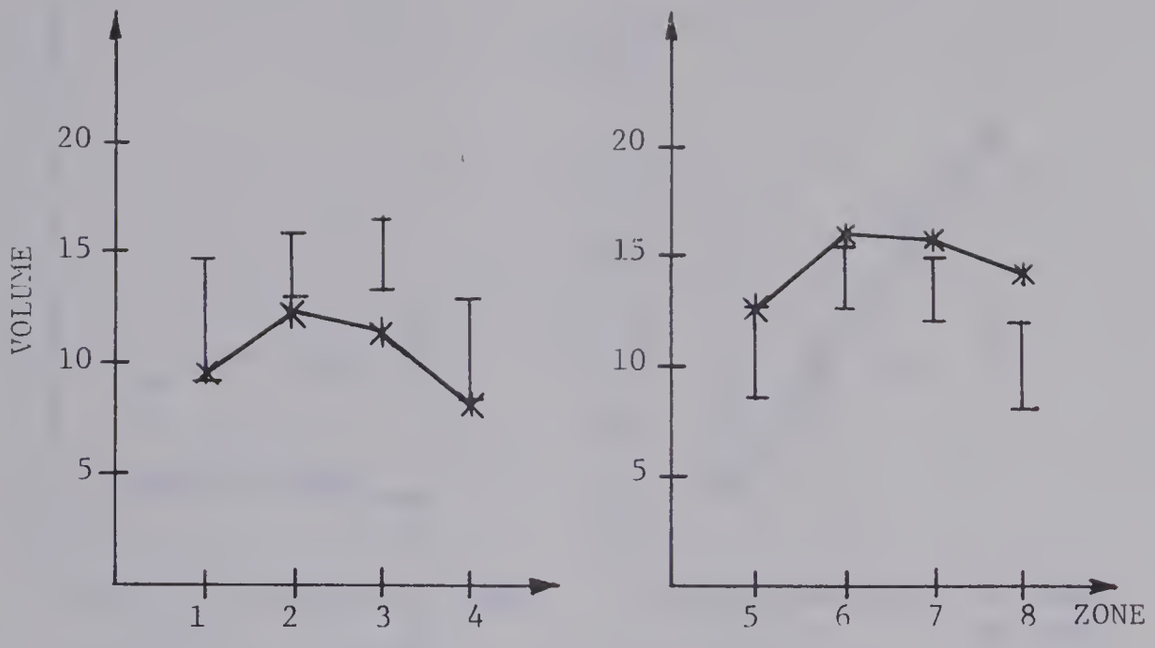

FIGURE 7-13 EXAMPLE OF DISEASED LUNGS

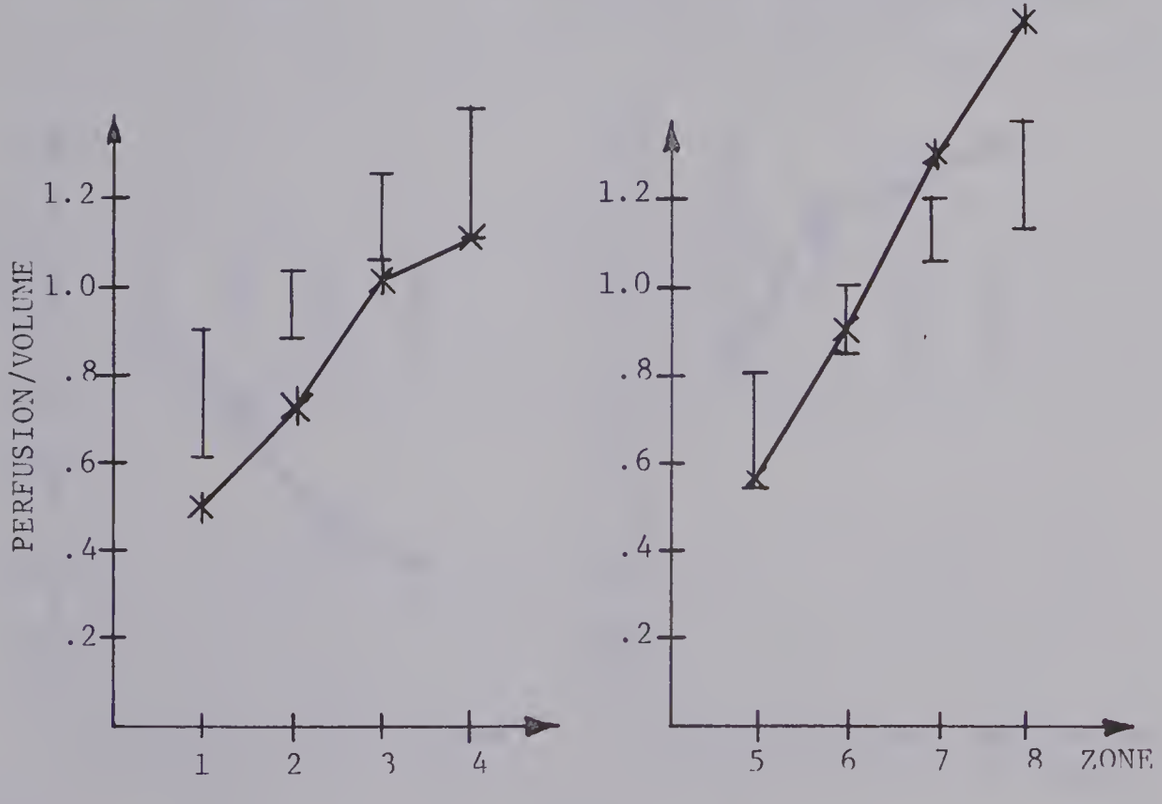

FIGURE 7-14 EXAMPLE OF DISEASED LUNGS

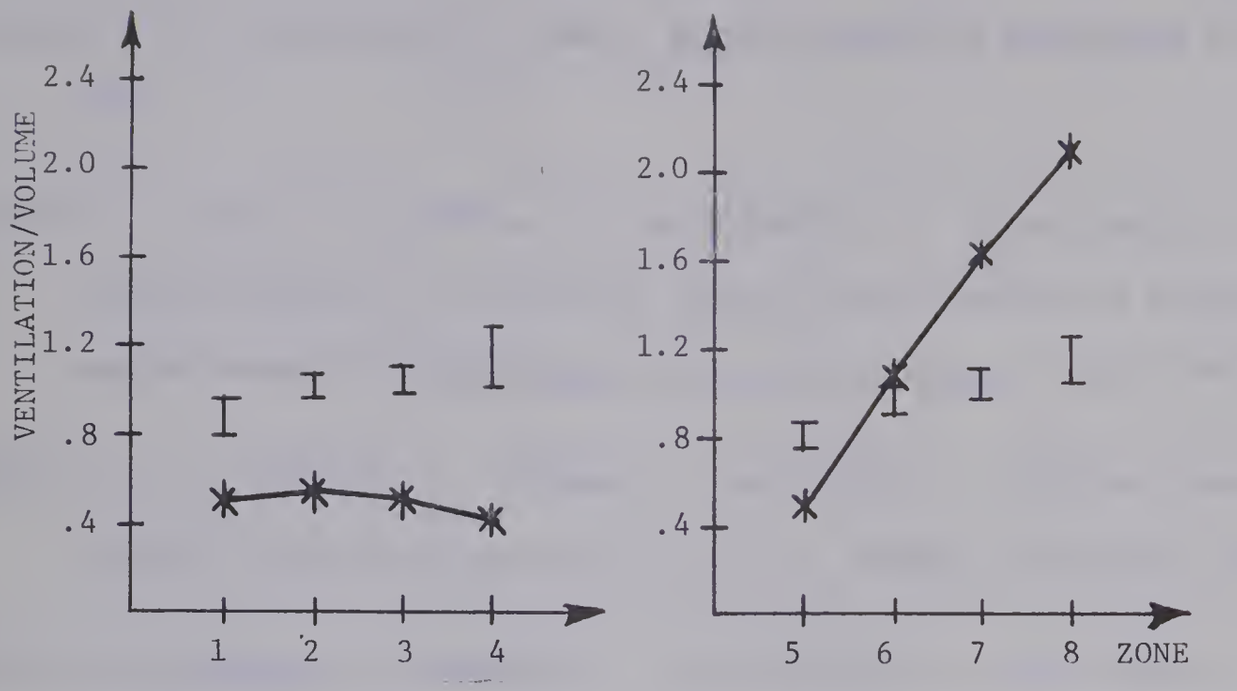

FIGURE 7-15 EXAMPLE OF DISEASED LUNGS

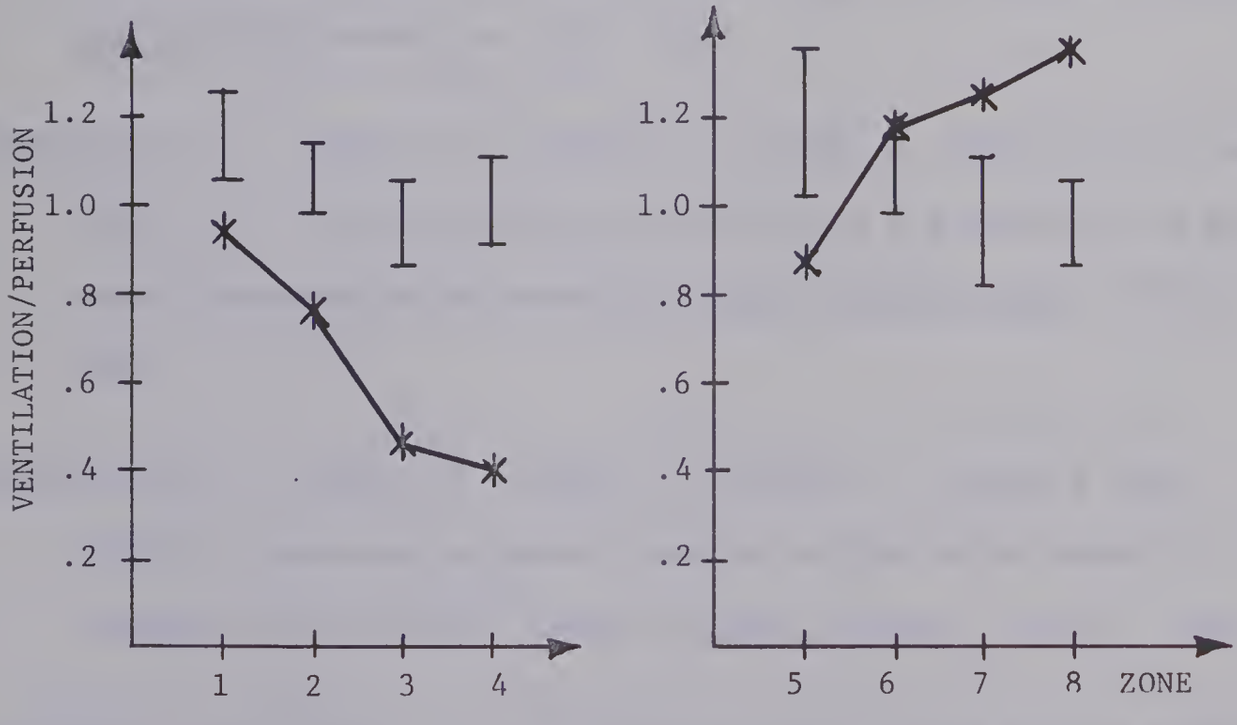

FIGURE 7-16 EXAMPLE OF DISEASED LUNGS

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C       DATA ANALYSIS OF XENON(133) - VENTILATION AND PERFUSION
C
C       UNIVERSITY OF ALBERTA .... APRIL 1971
C       FOR USE ON IBM 360/67 COMPUTER OPERATING UNDER THE
C            MICHIGAN TERMINAL SYSTEM
C            (PROGRAM IS INTERACTIVE)
C
C       DATA IS CONTAINED ON MAGNETIC TAPE IN FORMAT 160014,
             PRECEDED BY A 6 DIGIT TAGWORD IDENTIFIER
C
        DIMENSION IY(200), KTAG(6), SAVE(8,6,2),  IS(200)
        COMMON /THREE/ SAVE,K2,KTAG
        COMMON /FOUR/ IDATA(8,200),JPTS(8)
        COMMON /ONE/ IY,TIME,IS
C
C          TIME STORES TIME BASE, FOR REPORTING 200 CHANNELS
        DIMENSION LPHA(27)
        INTEGER UNIT, LIST(3)/2,215,218/
        INTEGER RE
        LOGICAL TAPE
        TAPE=.FALSE.
        DATA RE/'REW'/
        INTEGER TAGWD,SUM,TAG,END
        DATA END/'END'/
        DATA SUM/3HSUM/
        DATA KOK/'OK'/
        DATA KBACK/'BAC'/
        DATA KYES/'YES'/
        UNIT=3
        GO TO 2
343     WRITE(6,22)
        GO TO 7
2       CONTINUE
C
C           PRINT OUT INITIAL INFORMATION ON THE TERMINAL
        WRITE (6,25)
1       WRITE(6,23)
        READ(5,45)ITRACK
        GO TO (1,1,1,1,1,1,3,1,100),ITRACK
        GO TO 1
100     TAPE=.TRUE.
3       WRITE (6,24)
        K2=0
        DO 5 K=1,6
5       KTAG(K)=0
C
C                SET REPORT AREA TO ZERO
        DO 6 J=1,8
        DO 6 J1=1,6
        DO 6 J2=1,2
6       SAVE(J,J1,J2)=0
        KERR=0
7       CALL GETIHC(IERR,LIST,&343)
C
C          ENTER INITIAL COMMAND - COMMENT,END,SUMMARY,REWIND,BACKSPACE
```

```
      WRITE (6,46)
      READ (5,47) LPHA
      IF (LPHA(1).EQ.KBACK) GO TO 4
      IF (LPHA(1).EQ.END) GO TO 20
      IF (LPHA(1).EQ.SUM) GO TO 19
      IF (LPHA(10.NE.RE) GO TO 8
      REWIND 1
      go to 7
4     DO 500 I=1,5
500   BACKSPACE 1
      GO TO 7
C
C                  ENTER REQUIRED TAGWORD FROM TERMINAL
8     CONTINUE
      WRITE (6,40)
      READ (5,26) TAG
      IF ((KERR.EQ.0).AND.(.NOT.TAPE)) READ (1,26) TAGWD,
     1((IDATA(JJ,J) ,J=1,200),JJ=1,8)
      IF ((KERR.EQ.0).AND.TAPE) READ (1,27) TAGWD,
     1((IDATA(JJ,J),J=1,200),JJ=1,8)
9     IF (TAGWD.EQ.TAG) GO TO 12
C
C        TAPE IS NOT POSITIONED TO REQUIRED TAGWORD
      WRITE(6,35)
      READ (5,47) IN
      IF (IN.NE.KYES) GO TO 11
C
C       YES,POSITION TAPE TO REQUIRED TAGWORD
10    IF(.NOT.TAPE)READ (1,26) TAGWD,
     1((IDATA(JJ,J),J=1,200),JJ=1,8)
      IF(TAPE)READ(1,27)TAGWD,((IDATA(JJ,J),J=1,200),JJ=1,8)
      IF (TAGWD.EQ.TAG) GO TO 12
      IF(TAGWD.LT.TAG)GO TO 10
      WRITE(6,53)TAGWD,TAG
      GO TO 7
11    CONTINUE
C
C          NO, DO NOT POSITION TAPE   PRINT OUT TAGWORD ON TAPE
      WRITE (6,51) TAG,TAGWD
      READ (5,26) TAG
      IF (TAG.EQ.9) GO TO 7
      GO TO 9
12    CONTINUE
      WRITE (6,44)
      READ (5,45) KODE
      TIME=0
      WRITE(6,42)
      READ (5,43) TIME
C
C        VERIFY THAT TERMINAL ENTRIES ARE CORRECT
400   WRITE (6,31)
      READ (5,30) IN
      IF (IN.NE.KOK) KERR=1
      IF (IN.NE.KOK) GO TO 7
      WRITE (UNIT,29) TAG
```

```
      KERR=0
      WRITE (UNIT,32) LPHA
C
C           ALLOW FOR UP TO 3 SETS OF SINGLE BREATH DATA
      IF (KODE.NE.2) KTAG(KODE)=TAG
      IF (KODE.EQ.2.AND.K2.EQ.0) KTAG(KODE)=TAG
      IF (KODE.EQ.2.AND.K2.NE.0) KTAG(K2+4)=TAG
C
C            CHANGE TIME TO A PER CHANNEL FIGURE
      TIME=TIME/200.0
            CALL SMOOTH
      GO TO (13,14,15,16), KODE
      WRITE(6,54)
      GO TO 12
13    WRITE (6,34)
      WRITE(UNIT,34)
      CALL PERF
      CALL SINGLE(KODE)
      GO TO 7
14    WRITE (6,36)
      WRITE(UNIT,36)
      K2=K2+1
      CALL SINGLE (KODE)
      GO TO 7
15    WRITE(6,37)
      WRITE(UNIT,37)
      CALL SINGLE (KODE)
      GO TO 7
16    WRITE (6,38)
      WRITE(UNIT,38)
      CALL SINGLE(KODE)
      GO TO 7
19    CONTINUE
      WRITE (6,33)
      CALL SUMM
      GO TO 3
20    CONTINUE
      WRITE (6,48)
C
C        TYPES OF DATA SET
C          PERFUSION =1
C          SINGLE BREATH =2
C          WASHIN = 3
C          WASHOUT = 4
C
21    CONTINUE
      STOP
C
22    FORMAT ('TAPE READ ERROR')
23    FORMAT ('0--7 OR 9 TRACK TAPE?')
24    FORMAT ('0****NEW SET OF DATA****'//)
25    FORMAT (1H1,'DATA ANALYSIS OF XENON(133)'//5X,15HTYPES OF CURVES
     1/7X,20H1 = PERFUSION       /7X,20H2 = SINGLE BREATH   /7X,20H3 = W
     2ASHIN          /7X,20H4 = WASHOUT         )
26    FORMAT (I6,8(20OI4))
```

```
27     FORMAT (2X,I6,8(20014))
28     FORMAT (1X,10F8.1)
29     FORMAT (1H1,'TAGWORD IS',I7)
30     FORMAT (A2)
31     FORMAT (' --ENTER OK TO CONFIRM THE ABOVE')
32     FORMAT (1X,27A3)
33     FORMAT (1HO,'**SUMMARIZE RESULTS OF PRECEDING DATA**')
34     FORMAT (1X,13H**PERFUSION**/)
35     FORMAT (1X,'--ENTER YES TO SCAN TAPE FOR TAGWORD')
36     FORMAT (1X,17H**SINGLE BREATH**/)
37     FORMAT (1X,10H**WASHIN**/)
38     FORMAT (1X,11H**WASHOUT**/)
40     FORMAT (1X,15H--ENTER TAGWORD)
42     FORMAT (1X,18H--ENTER TIME(SECS))
43     FORMAT (F10.2)
44     FORMAT (1X,26H--ENTER CURVE TYPE CODE   )
45     FORMAT (I1)
46     FORMAT (1HO,'--COMMENT, END, SUMMARY, REWIND,'
      1 ' BACKSPACE')
47     FORMAT (27A3)
48     FORMAT (1H1,15HEND OF ANALYSIS)
51     FORMAT (3X,16HUNEQUAL TAGWORDS,2I10/1X,42H--ENTER NEW TAGWORD OR 0
      10009 FOR CANCEL  )
53     FORMAT ('0--PRESENT TAGWORD IS',I8,'; WE MUST HAVE PASSED TAGWORD'
      1,I8)
54     FORMAT ('0--ILLEGAL CURVE TYPE')
       END
```

```
      SUBROUTINE SMOOTH
C
C     DATA SMOOTHING PROCEDURE
      DIMENSION Z(200), JPTS(8), IDATA(8,200)
      COMMON /FOUR/ IDATA, JPTS
      DO 5 JJ=1,8
      JPTS(JJ)=0
      DO 3 J=1,200
      SUM=0.0
      DEV=0.0
      IF (J.GT.196) GO TO 3
C
C     FIRST LOCATE POINTS WHICH ARE ABNORMALLY HIGH OR LOW
      DO 1 I=1,5
      IF (I.EQ.3) GO TO 1
      SUM=SUM+IDATA(JJ,J+I-1)
1     CONTINUE
      SUM=SUM/4.0
      DO 2 I=1,5
      IF (I.EQ.3) GO TO 2
      DEV=DEV+(IDATA(JJ,J+1)-SUM)**2
2     CONTINUE
      DEV=10.0*SORT(DEV/3.0)
      IF (ABS(IDATA(JJ,J+2)-SUM).LE.DEV) GO TO 3
C
C     CORRECT ABNORMAL DATA POINTS
      IDATA(JJ,J+2)=SUM
      JPTS(JJ)=JPTS(JJ)+1
3     Z(J)=IDATA(JJ,J)
      CALL SE15 (Z,Z,200,IER)
      DO 4 J=1,200
4     IDATA(JJ,J)=Z(J)
5     CONTINUE
      RETURN
      END
```

```
C   LINEAR SMOOTHING PROCEDURE
      SUBROUTINE SE15(Y,Z,NDIM,IER)
C
      DIMENSION Y(200),Z(200)
      IF(NDIM-5)3,1,1
C
C   PREPARE LOOP
1     A=Y(1)+Y(1)
      C=Y(2)+Y(2)
      B=.2*(A+Y(1)+C+Y(3)-Y(5))
      C=.1*(A+A+C+Y(2)+Y(3)+Y(4))
C
C   START LOOP
      DO 2 I=5,NDIM
      A=B
      B=C
      C=.2*(Y(I-4)+Y(I-3)+Y(I-2)+Y(I-1)+Y(I))
2     Z(I-4)=A
C   END OF LOOP
C
C   UPDATE LAST FOUR COMPONENTS
      A=Y(NDIM)+Y(NDIM)
      A=.1*(A+A+Y(NDIM-1)+Y(NDIM-2)+Y(NDIM-2)+Y(NDIM-1)
     1+Y(NDIM-3))
      Z(NDIM-3)=B
      Z(NDIM-2)=C
      Z(NDIM-1)=A
      Z(NDIM)-A+A-C
      IER=0
      RETURN
C
C   ERROR EXIT IN CASE NDIM IS LESS THAN 5
3     IER=-1
      RETURN
      END
      END$
```

```
      SUBROUTINE PERF
C
C     DETECTION OF ARTEFACTS DUE TO INJECTION
      COMMON /TWO/ KCH,BREAK
      COMMON /FOUR/ IDATA(8,200),JPTS(8)
C
C       SCAN DATA TO FIND ARTEFACT PEAKS
      INTEGER TAG(7),KDIF(7),PK(8),BREAK,BRKPT
      DO 1 JJ=1,8
      PK(JJ)=0
      MAX=0
      DO 1 J=1,200
      IF (IDATA(JJ,J).LE.MAX) GO TO 1
      MAX=IDATA(JJ,J)
      PK(JJ)=J
1     CONTINUE
C
C        ARE ALL THE PEAKS IN THE SAME GENERAL AREA?
C        FIND DIFFERENCES
      MAX=0
      DO 2 J=1,8
      IF (PK(J).LE.MAX) GO TO 2
      MAX=PK(J)
      NPVT=J
2     CONTINUE
      L=0
      DO 3 J=1,8
      IF (NPVT.EQ.J) GO TO 3
      L=L+1
      TAG(L)=J
      KDIF(L)=IABS(MAX-PK(J))
3     CONTINUE
C
C             ARRANGE DIFFERENCES IN ASCENDING ORDER
      DO 4 L=1,7
      DO 4 J=1,6
      IF (KDIF(J).LE.KDIF(J+1)) GO TO 4
      KTEMP=KDIF(J)
      KDIF(J)=KDIF(J+1)KDIF(J+1)=KTEMP
      KTEMP=TAG(J)
      TAG(J)=TAG(J+1)
      TAG(J+1)=KTEMP
4     CONTINUE
C
C          FIND THE LARGEST SPREAD IN DIFFERENCES
      BREAK=0
      DO 5 J=1,6
      KSUB=KDIF(J+1)-KDIF(J)
      IF(KSUB.LE.BREAK) GO TO 5
      BREAK=KSUB
      NNN=J
      BRKPT=TAG(J+1)
5     CONTINUE
C
```

```
C       IS THERE A SIGNIFICANTLY LARGE SPREAD AT LARGEST DIFFERENCE?
        IF (NNN.LE.3) GO TO 8
        DEV=0.0
        SUM=0.0
        DO 6 N=1,NNN
6       SUM=SUM+KDIF(N)
        SUM=SUM/NNN
        DO 7 N=1,NNN
7       DEV=DEV+(KDIF(N)-SUM)**2
        DEV=SUM+SQRT(DEV/(NNN-1))
        IF (FLOAT(BREAK).GT.DEV) GO TO 9
8       KCH=1
C
C            DEFAULT:  ARTEFACT AT CHANNEL 1
        WRITE (3,10)
        RETURN
9       KCH=PK(BRKPT)
        MM=NNN+1
        WRITE (3,11) KCH,(TAG(N),N=MM,7)
C
C          BECAUSE OF THE ASCENDING ORDER OF THE DIFFERENCES
C           THIS WILL ALLOW FOR ARTEFACTS IN MORE THAN ONE DETECTOR
        RETURN
C
10      FORMAT (' NO ARTEFACTS WERE FOUND'/)
11      FORMAT (' ARTEFACT IN CHANNEL ',17,8X,'DETECTOR',414/)
        END
```

```
      SUBROUTINE EXTRCT (MX,NO,INIT)
C
C        EXTRACT LARGEST ELEMENT FROM DATA SET
C        MX HOLD LARGEST ELEMENT
C        NO HOLDS X-POSITION OF MX
      COMMON /ONE/ IY,TIME,IS,LONG
      DIMENSION IY(200), IS(200)
      MX=0
      DO 1 J=INIT,195
      IF (IY(J).LE.MX) GO TO 1
      IF (IS(J).EQ.0) GO TO 1
      MX=IY(J)
      NO=J
1     CONTINUE
      IS(NO)=0
      RETURN
      END
```

```
      SUBROUTINE SINGLE (TYPE)
C
C  ANALYSES A PARTICULAR SET OF CURVES
      IT=3
      COMMON /ONE/ IX,TIME,IS
      DIMENSION IDATA(8,200),A(2),C(2)
      COMMON /TWO/ KCH,BREAK
      COMMON /THREE/ SAVE,KKATE,KTAG
      COMMON /FOUR/ IDATA,JPTS(8)
      DIMENSION KPT(8), SAVE(8,6,2), KTAG(6)
      DIMENSION IX(200), KPOS(6), IS(200)
      INTEGER BREAK,REJ,ENDD,TYPE,HT,HALF,START
      DIMENSION H(4), IY(6)
      INTEGER LIST(2)/1,253/
C
C  SET UP ERROR RECOVERY PROCEDURE
      CALL GETIHC(IERR,LIST,&202)
      WRITE(IT,54)
      DO 39 JJ=1,8
      REJ=0
      DO 2 J=1,200
2     IX(J)=IDATA(JJ,J)
      DO 9 J=1,200
9     IS(J)=1
C
C        IN PERFUSION CURVE - OMIT ARTEFACT PEAK
      INIT=2
      IF (TYPE.NE.1) GO TO 11
      IS(KCH)=0
      INIT=KCH+BREAK
C
C          CALCULATE BKG FOR SINGLE BREATH
11    VBACK=0
      DO 12 J=2,13
12    VBACK=VBACK+IX(J)
      KVBACK=VBACK/12.0
13    CONTINUE
C
C        FIND 1ST AND 2ND LARGEST IX VALUES
      CALL EXTRCT (M2,N2,INIT)
      IF(TYPE.NE.2)GO TO 100
14    CONTINUE
      CALL EXTRCT (M3,N3,INIT)
      LENG=IABS(N2-N3)
      IF(LENG.GT.20)REJ=REJ+1
      IF (LENG.GT.20) GO TO 14
      IY(1)=M2
      KPOS(1)=N2
      KPOS(2)=N3
      IY(2)=M3
C
C        FIND 6 LARGEST POINTS IN THIS NEIGHBORHOOD OF LENGTH 32 to 50
      K=2
16    CALL EXTRCT (M,N,INIT)
```

```
      LEN1=IABS(N-N2)
      LEN2=IABS(N-N3)
      IF (LEN1.LE.15.OR.LEN2.LE.15) GO TO 17
      REJ=REJ+1
      GO TO 16
17    K=K+1
      IY(K)=M
      KPOS(K)=N
      IF (K.LT.6) GO TO L6 '
C
C        FIND HEIGHT
      HT=0
      DO 18 J=1,K
18    HT=HT+IY(J)
C
c        MAX HEIGHT
      HT=HT/K
C
C        TIME TO MAX HEIGHT
C         FIRST BUBBLE SORT
      DO 19 KNO=1,K
      KK=K-1
      DO 19 J=1,KK
      IF (KPOS(J).LE.KPOS(J+1)) GO TO 19
      KC=KPOS(J)
      KPOS(J)=KPOS(J+1)
      KPOS(J+1)=KC
      KC=IY(J)
      IY(J)=IY(J+1)
      IY(J+1)=KC
19    CONTINUE
C
C       FIND 4 SMALLEST INTERVALS
      L=0
      DO 23 JJJ=1,4
      INTR=100
      DO 22 J=1,KK
      IF (JJJ.EQ.1) GO TO 21
      LM=2*JJJ-3
      DO 20 LL=1,LM,2
      IF (KPOS(J).EQ.KPT(LL)) GO TO 22
20    CONTINUE
21    CONTINUE
      NINT=IABS(KPOS(J+1)-KPOS(J))
      IF (NINT.GE.INTR) GO TO 22
      INTR=NINT
      K1=KPOS(J)
      K2=KPOS(J+1)
22    CONTINUE
      L=L+1
      KPT(L)=K1
      L=L+1
      KPT(L)=K2
23    CONTINUE
```

```
      KSUM=0
      DO 24 J=1,L
24    KSUM=KSUM+KPT(J)
      MED=KSUM/L
      H(1)=TIME*MED
C
C          ONLY ONE SET OF DATA SHOULD BE ENTERED FOR
                  PERFUSION, WASH-IN, AND WASH-OUT
C       TEST FOR NUMBER OF SINGLE BREATH SETS OF DATA
      IF (KKATE.LE.3) GO TO 25
      WRITE (6,52)
      KKATE=KKATE-1
      RETURN
25    CONTINUE
      CORR=1E20
      A(1)=1E20
      A(2)=1E20
      C(1)=1E20
      C(2)-1E20
      JH=9999999
      HALF=9999999
      NCOMP=0
      HT=HT-KVBACK
      IF (KKATE.EQ.1) SAVE(JJ,TYPE,1)=HT
      IF (KKATE.NE.1) SAVE(JJ,KKATE+3,1)=HT
      GO TO 36
C
C        PERFUSION CURVE ANALYSIS
99    DO 98 II=1,200
98    IX(II)=IX(II)-KVBACK
      KVEND=HT
      MED=N2
      JKK=MED+1
      JKL=MED+20
      A(2)=1E20
      C(2)=1E20
      NCOMP=1
      CALL FIT(A,C,1,JKK,JKL,CORR)
      HT=M2-KVBACK
      HT2=HT/2+KVEND/4
      HALF=(ALOG(HT2)-ALOG(C(1)))/A(1)
      GO TO 37
100   IF ((TYPE.NE.3).AND.(TYPE.NE.1)) GO TO 29
C
C          WASHIN CASE - FIND WHERE CURVE STARTS AND ENDS
      KL=201
101   KL=KL-1
      IF(IX(KL).LE.0)GO TO 101
      KL=KL-5
      KB+KL-19
      HT=0
      IF(KB.LE.0)GO TO 201
      DO 102 KK=KB,KL
102   HT=HT+IX(KK)
      HT=HT/20
      IF(TYPE,EQ.1)GO TO 99
```

```
      KDEV=2.0*SQRT(FLOAT(KVBACK))
      J=10
      DO 28 II=1,3
27    J=J+1
      IF(IX(J).LE.(KVBACK+KDEV))G) TO 27
28    CONTINUE
      J=J-2
      DO 110 II=1,200
110   IX(II)=HT-IX(II)
      HT=HT-KVBACK
      JF=J+13
      A(2)=1E20
      C(2)-1E20
      NCOMP=1
      CALL FIT(A,C,1,J,JF,CORR)
      JSTART=(ALOG(FLOAT(HT))-ALOG(C(1)))/A(1)
      HT2=HT/2.0
      HALF=(ALOG(HT2)-ALOG(C(1)))/A(1)
      MED=JSTART
      GO TO 37
C
C       WASHOUT CASE  -  FIND WHERE THE CURVE STARTS
29    HT=KVBACK
      XHT=HT
      J=10
      KDEV=4*SQRT(XHT)
      DO 31 LK=1,5
30    J=J+1
      IF (IX(J).GE.HT-KDEV) GO TO 30
31    CONTINUE
      MED=J-4
      NCOMP=2
      CALL FIT(A,C,2,MED,200,CORR)
      IF(C(2).GT.0.0)GO TO 34
      NCOMP=1
      C(2)=C(1)
      C(1)=0.
      A(2)=A(1)
      A(1)=0.
C
C    FIND T-ZERO FOR WASHOUT
34    MED=MED-1
33    BACK=C(1)*EXP(A(1)*MED)
      CORHT=XHT-BACK
      HT2=CORHT/2.0
      HALF=(ALOG(HT2)-ALOG(C(2)))/A(2)
37    CONTINUE
      H(1)=TIME*MED
      H(2)=TIME*HALF
      SAVE(JJ,TYPE,1)=HT
      SAVE(JJ,TYPE,2)=ABS(H(2)-H(1))
      JH=HT2
      IF(SAVE(JJ,TYPE,2).EQ.0)SAVE(JJ,TYPE,2)=1
36    WRITE (IT,55)JJ,CORR,A(1),C(1),A(2),C(2),HT,MED,JH,HALF,NCOMP,
     1JPTS(JJ),REJ
39    CONTINUE
```

```
      RETURN
201   WRITE(6,56)
      RETURN
202   WRITE(6,57)
      RETURN
C
54    FORMAT('-DET CORR',T19,'FITTED CURVE',T41,'MAXIMUM   HALF MAX',
     1'  COMP ERRORS'/' ',T14,'A1',5X,'C1',5X,'A2',5X,'C2',4X,
     2'HT  CHAN   HT  CHAN',T66,'AVG REJ')
55    FORMAT('0',I2,F7.2,2(F7.3,F7.0),2(I5,I4,2X),I4,I3,I4)
52    FORMAT ('0MORE THAN 3 SETS OF SINGLE BREATH DATA'/
     1'RETURN TO CALLING PROGRAM'/)
56    FORMAT('-INCOMPLETE DATA SET; ANALYSIS ABORTED.')
57    FORMAT('-NEGATIVE ARGUMENT FOR LOG; ANALYSIS ABORTED')
      END
```

```
      SUBROUTINE FIT(A,C,NCOMP,NS,NE,R)
C
C  EXPONENTIAL CURVE FITTING
C
      COMMON/TEN/ DATA(200)
      COMMON/ONE/NDATA
      DIMENSION NDATA(200),SDATA(200),A(1),C(1)
      LOGICAL LOG
      LOG=.FALSE.
      JTEST=0
      NF=NE
C
C  FIND END OF USEFUL DATA
      DO 10 I=NS,NF
      IF(NDATA(I).LE.0)GO TO 5
      XDATA(I)=NDATA(I)
C
C  TAKE LOGARITHMS OF DATA POINTS
10    DATA(I)=ALOG(XDATA(I))
      GO TO 6
5     NF=I-5
6     NBEG=NF-25
      IF((NF-NS).LT.9)GO TO 75
      DO 30 K=1,NCOMP
      IF(K.EQ.1)GO TO 3
C
C  IF CURVE IS MULTI-EXPONENTIAL, SUBTRACT PREVIOUS COMPONENT
      DO 2 I=NS,NF
      XDATA(I)=XDATA(I)-EXP(A1*I+B1)
      IF(XDATA(I).LE.0.0)GO TO 20
2     DATA(I)=ALOG(XDATA(I))
20    JF=I-1
      NBEG=NS
      GO TO 4
3     JF=NF
      IF(LOG)NBEG=NS
      LOG=.FALSE.
4     IF(NBEG.LE.NS)NBEG=NS
      IF(JF-NBEG).LT.9)LOG=.TRUE.
      IF(K.EQ.NCOMP)NBEG=NS
      IF(LOG)GO TO 6
      IF((K.EQ.NCOMP).AND.(JF.GT.(NBEG+25)))JF=NBEG+25
50    CALL LSQ(NBEG,JF,1.0,A1,B1,R)
      IF(A1.GT.0.0)NBEG=NBEG-1
      JTEST=JTEST+1
      IF(JTEST.GT.25)GO TO 76
      IF(A1.GT.0.0)GO TO 50
      A(K)=A1
      C(K)=EXP(B1)
      IF(NBEG.EQ.NS)GO TO 52
30    CONTINUE
52    IF(K.EQ.NCOMP)GO TO 70
      KK=K+1
      DO 65 L=KK,NCOMP
```

```
      A(L)=0.0
65    C(L)=0.0
70    CONTINUE
      RETURN
75    WRITE(6,100)
      RETURN
76    WRITE(6,101)
      RETURN
100   FORMAT(' I WANT AT LEAST 10 POINTS FOR CURVE FITTING.')
101   FORMAT(' MORE THAN 50 POINTS REQUIRED FOR SLOW COMPONENT')
      END
```

```
      SUBROUTINE LSQ(NS,NF,T,A,B,R)
C
C  LEAST SQUARES REGRESSION LINE
      COMMON/TEN/ DATA(200)
      REAL*8 SX,SY,SX2,SY2,SXY
      SX=0.0
      SY=0.0
      SX2=0.0
      SY2=0.0
      SXY=0.0
      PTS=FLOAT(NF-NS+1)
      DO 2 I=NS,NF
      SX=SX+T*FLOAT(I)
      SY=SY+DATA(I)
      SX2+SX2+T*FLOAT(I))**2
      SY2=SY2+(DATA(I))**2
      SXY=SXY+DATA(I)*T*FLOAT(I)
    2 CONTINUE
      A=(PTS*SXY-SX*SY)/(PTS*SX2-SX**2)
      B=((SY-A*SX(/PTS)
C
C  CALCULATION OF CORRELATION COEFFICIENT
      R=DABS(((PTS*SXY-SX*SY)**2)/((PTS*SX2-SX**2)*(PTS*SY2-SY**2)))
      R=SQRT(R)
      RETURN
      END
```

```
      SUBROUTINE SUMM
C
C        SUMMARY GENERATOR
C
      COMMON IY(200),TIME,IS(200),KCH,KBREAK,SAVE,K2,KTAG,IDATA(8,200),J
     1PTS(8),DATA(200),KODE
      DIMENSION SAVE(8,6,2), XK(8), QSUM(2), QDOT(8), QDIVV(8), KTAG(6),
     1 KWHR(8,6), AVG(8,6)
      REAL LINE(8,5)
      REAL KTAG
      INTEGER WASH1(3)
      WASH 1(2)=2HWA
      WASH 1(2)=2HSH
      WASH 1(3)=2H1
      IT=6
C
C     INITIALIZE CHARACTER ARRAYS
C
      DO 1 I=1,4
      KWHR(I,1)=2HRI
      KWHR(I,2)=2HGH
1     KWHR(I,3)=2HT
      DO 2 I=5,8
      KWHR(I,1)=2HLE
      KWHR(I,2)=2HFT
      KWHR(I,3)=2H
2     CONTINUE
      DO 3 I=1,5,4
      KWHR(I,4)=2HAP
      KWHR(I,5)=2HEX
      KWHR(I,6)= 2H
      KWHR(I+1,4)=2HUP
      KWHR(I+1,5)=2HPE
      KWHR(I+1,6)=2HR
      KWHR(I+2,4)=2HLO
      KWHR(I+2,5)=2HWE
      KWHR(I+2,6)=2HR
      KWHR(I+3,4)=2HBA
      KWHR(I+3,5)=2HSE
      KWHR(I+3,6)=2H
3     CONTINUE
C
C        CHECK FOR PRESENCE OF PERFUSION DATA
C
      IF (SAVE(1,1,1).GT.0.0) GO TO 4
      WRITE (1,26)
      CALL EXEC (8,WASH1)
C
C        CHECK FOR PRESENCE OF WASHIN DATA
C
4     IF (SAVE(1,3,1).GT.0) GO TO 5
      WRITE (1,27)
      CALL EXEC (8,WASH1)
5     CONTINUE
```

```
C
C        CALCULATE VOLUME NORMALIZING PARAMETERS FROM WASHIN DATA
C
      S=Ø
      DO 6 J=1,8
6     S=S+SAVE(J,3,1)
      WRITE (IT,28)
      DO 7 J=1,8
7     XK(J)=SAVE(J,3,1)/S
C
C        PERFUSION CURVE
C
      WRITE (IT,32) KTAG(1)
      WRITE (IT,34)
      S=Ø
      DO 8 J=1,8
8     S=S+SAVE(J,1,1)
      L=1
      QSUM(1)=0
      QSUM(2)=0
      DO 9 J=1,8
      QDOT(J)=SAVE(J,1,1)/S
      QDIVV(J)=QDOT(J)/XK(J)
      IF (J.GT.4) L=2
      QDOT(J)=QDOT(J)*100.0
      QSUM(L)=QSUM(L)+QDOT(J)
      WRITE (IT,39) (KWHR(J,M),M=1,6), QDOT(J),QDIVV(J)
      IF (J.EQ.4.OR.J.EQ.8)  WRITE (IT,40) QSUM(L)
9     CONTINUE
      WRITE (IT,29)
C
C        PERFUSION WASH-OUT
C
      WRITE (IT,33) KTAG(1)
      WRITE (IT,35)
      WRITE (IT,36)
      XMCR=Ø
      DO 1Ø J=1,8
      LINE(J,1)=SAVE(J,1,2)
      LINE(J,2)=XK(J)/SAVE(J,1,2)
10    XMCR=XMCR+LINE(J,2)
      VSUM=0.0
      DO 11 J=1,8
      LINE(J,3)=1.Ø/SAVE(J,1,2))/XMCR
      LINE(J,4)=LINE(J,3)/QDIVV(J)
      VENT=XK(J)*LINE(J,3)*1ØØ.Ø
      WRITE (IT,31)  (KWHR(J,M),M=1,6),VENT,(LINE(J,M),M=1,4)
      VSUM=VSUM+VENT
      IF (J.NE.4) GO TO 11
      WRITE (IT,42) VSUM
      VSUM=Ø.Ø
11    CONTINUE
      WRITE (IT,44) VSUM,XMCR
C
C        SINGLE BREATH
```

```
C
12    CONTINUE
      IF (SAVE(1,2,1).LE.Ø.ØØØØ1) GO TO 18
      NP1=Ø
      KPL=2
      IF (K2.NE.3) WRITE (IT,28)
      IF (K2.EQ.3) WRITE (IT,37)
13    CONTINUE
      IF (NP1.NE.Ø) WRITE (IT,29)
      WRITE (IT,32) KTAG(KPL)
      WRITE (IT,38)
      S=Ø
      DO 14 J=1,8
14    S=S+SAVE(J,KPL,1)
      L=1
      QSUM(1)=Ø
      QSUM(2)=Ø
      DO 17 J=1,8
      LINE(J,1)=SAVE(J,KPL,1)/S
      LINE(J,2)=LINE(J,1)/XK(J)
      LINE(J,3)=LINE(J,2)/QDIVV(J)
      IF (J.GT.4) L=2
      LINE(J,1)=LINE(J,1)*1ØØ.Ø
      QSUM(L)=QSUM(L)+LINE(J,1)
      WRITE (IT,39) (KWHR(J,M),M=1,6),(LINE(J,M),M=1,3)
      IF (KPL.NE.2) GO TO 16
      DO 15 NN=1,3
15    AVG(J,NN)=LINE(J,NN)
16    IF (J.EQ.4.OR.J.EQ.8) WRITE (IT,40) QSUM(L)
17    CONTINUE
      IF (K2.EQ.1) GO TO 18
      IF (KPL.EQ.5.AND.K2.EQ.2) GO TO 18
      NP1=NP1+1
      IF (NP1.GE.3) GO TO 18
      KPL=4+NP1
      GO TO 13
C
C        WASHIN CURVE
C
18    CONTINUE
      WRITE (IT,28)
      WRITE (IT,33) KTAG(3)
      WRITE (IT,30)
      XMCR=Ø
      DO 19 J=1,8
      LINE(J,1)=XK(J)/SAVE(J,3,2)
19    XMCR=XMCR+LINE(J,1)
      L=1
      QSUM(1)=Ø
      QSUM(2)=Ø
      VSUM=Ø
      DO 2Ø J=1,8
      LINE(J,2)=1.Ø/SAVE(J,3,2))/XMCR
      LINE(J,3)=LINE(J,2)/QDIVV(J)
```

```
      VENT=XK(J)*LINE(J,2)*1ØØ.Ø
      XX=XK(J)*1ØØ.Ø
      WRITE (IT,31) (KWHR(J,M),M=1,6),XX,SAVE)J,3,2),(LINE(J,M),M=1,3),V
     1ENT
      AVG(J,4)=VENT
      AVG(J,5)=LINE(J,2)
      IF (J.GE.5) L=2
      QSUM(L)=QSUM(L)+XX
      VSUM=VSUM+VENT
      IF (J.EQ.4) WRITE (IT,41) QSUM(L),VSUM
      IF (J.EQ.4) VSUM=Ø.Ø
      IF (J.EQ.8) WRITE (IT,43) QSUM(L),XMCR,VSUM
20    CONTINUE
C
C        WASHOUT CURVE
C
      IF (SAVE(1,4,1).LE.Ø.ØØØØ1) GO TO 23
      WRITE(IT,29)
      WRITE (IT,33) KTAG(4)
      WRITE (IT,36)
      XMCR=Ø
      DO 21 J=1,8
      LINE(J,1)=XK(J)/SAVE(J,4,2)
21    XMCR=XMCR+LINE(J,1)
      VSUM=Ø.Ø
      DO 22 J=1,8
      LINE(J,2)=(1.Ø/SAVE(J,4,2))/XMCR
      LINE(J,3)=LINE(J,2)/QDIVV(J)
      VENT=XK(J)*LINE(J,2)*1ØØ.Ø
      WRITE (IT,31) (KWHR(J,M),M=1,6),VENT,SAVE)J,4,2),(LINE(J,M),M=1,3)
      VSUM=VSUM+VENT
      IF (J.NE.4) GO TO 22
      WRITE (IT,42) VSUM
      VSUM=Ø.Ø
22    CONTINUE
      WRITE (IT,44) VSUM,XMCR
      WRITE (IT,29)
23    IF (SAVE(1,2,1).LE.Ø.ØØØØ1) CALL EXEC (8,WASH1)
C
C        CALCULATION OF AVERAGE INDICES OF VENTILATION
C
      WRITE (IT,28)
      WRITE (IT,45)
      L=1
      QSUM(1)=Ø.Ø
      QSUM(2)=Ø.Ø
      DO 25 J=1,8
      DO 24 JJ-1,3
24    AVG(J,JJ)=(AVG(J,JJ)+AVG(J,JJ+3))/2.Ø
      WRITE (IT,39) (KWHR(J,M),M=1,6),(AVG(J,M),M=1,3)
      IF (J.GE.5) L=2
      QSUM(L)=QSUM(L)+AVG(J,1)
      IF (J.EQ.4.OR.J.EQ.8) WRITE (IT,40) QSUM(L)
25    CONTINUE
```

```
      CALL EXEC (8,WASH1)
      CALL MAIN
C
26    FORMAT (" **NO PERFUSION DATA FOR SUMMARIZING**"/)
27    FORMAT (" **NO WASHIN DATA FOR SUMMARIZING**"/)
28    FORMAT (1H1/1HØ,15X,"UNIVERSITY OF ALBERTA HOSPITAL"/1X/1HØ,15X,
     1"XENON-133 REGIONAL PULMONARY FUNCTION REPORT"////
     2" TYPE OF CURVE*")
29    FORMAT (1HØ)
30    FORMAT (" WASH-IN",6X,"*",4X,"K".4X,"*",2X,"R1/2",2X,"*",3X,"K/T1/
     12",2X,"*",3X,"V./V",2X,"*",2X,"V./Q.",2X,"*",3X,"V."/" ",72("*"))
31    FORMAT (1X,6A2,1X,"*",F6.1,3X,"*",F6.1,2X,"*",F9.5,2X,"*",F7.3.2X,
     1"*",F7.3,2X,"*",F6.1)
32    FORMAT (1X,72("*")/1X,F6.0,7X,"*",9X,"*",8X,"*",11X,"*",9X,"*")
33    FORMAT (1X,72("*")/1X,F6.0,7X,"*",9X,"*",8X,"*",11X,"*",2(9X,"*"))
34    FORMAT (" PERFUSION",4X,"*",3X,"Q.",4X,"*",8X,"*",11X,"*",3X,"Q./V
     1",2X,"*"/" ",72("*"))
35    FORMAT (" PERFUSION",4X,"*",9X,"*",8X,"*",11X,"*",2(9X,"*"))
36    FORMAT (" WASH-OUT",5X,"*",3X,"V.",4X,"*",2X,"T1/2",2X,"*",3X,"K/T
     11/2",2X,"*",3X,"V./V",2X,"*",2X,"V./Q.",2X,"*"/1X,72("*"))
37    FORMAT ("1TYPE OF CURVE*")
38    FORMAT (" SINGLE BREATH*",3X,"V.",4X,"*",8X,"*",11X,"*",3X,"V./V",
     12X,"*",2X,"V./Q."/1X,72("*"))
39    FORMAT (1X,6A2,1X,"*",F6.1,3X,"*",8X,"*",11X,"*",Fj.3,2X,"*"F7.3)
4Ø    FORMAT (14X,"*",1X,6("-"),2X,"*"8X,"*",11X,"*",9X"*"/14X,"*",F6.1,
     13X,"*",8X,"*",11X,"*",9X,"*"/14X,"*",9X,"*",8X,"*",11X,"*",9X,"*")
41    FORMAT (14X,"*",1X,6("-"),2X,"*",8X,"*",11X,"*",2((X,"*"),1X,5("-")
     1)/14X,"*",F6.1,3X,"*",8X,"*",11X,"*",2(9X,"*"),F6.1/14X,"*",9X,"*"
     2,8X,"*",11X,"*",2(9X,"*"))
42    FORMAT (14X,"*",1X,6("-"),2X,"*",8X,"*",11X,"*",2(9X,"*")/14X,"*",
     1F6.1,3X,"*",8X,"*",11X,"*",2(9X,"*")/14X,"*",9X,"*",8X,"*",11X,"*"
     2,2(9X,"*"))
43    FORMAT (14X,"*",1X,6("-"),2X,"*",8X,"*",3X,6("-"),2X,"*",2(9X,"*")
     1,1X,5("-"0/14X,"*",F6.1,3X,"*",8X,"*",F9.5,2X,"*",2(9X,"*"),F6,1)
44    FORMAT (14X,"*",1X,6("-"),2X,"*",9X,"*",3X,6("-"),2X,"*",2(9X,"*")
     1/14X,"*",F6.1,3X,"*",8X,"*",F9.5,2X,"*",2(9X,"*"))
45    FORMAT (1X,72("*")/14X,"*",9X,"*",8X,"*",11X,"*",9X,"*"/" AVERAGES
     1",5X,"*",3X,"V.",4X,"*",8X,"*",11X,"*",3X,"V./V",2X,"*",2X,"V./Q,"
     2/1X,72("*"))
      END
      END$
```

SAMPLE OUTPUT

UNIVERSITY OF ALBERTA HOSPITAL

XENON-133 REGIONAL PULMONARY FUNCTION REPORT

TYPE OF CURVE			
104174. PERFUSION	Q.		Q./V
RIGHT APEX	9.3		.832
RIGHT UPPER	12.7		.887
RIGHT LOWER	17.9		1.199
RIGHT BASE	14.2		1.264

	54.1		
LEFT APEX	5.6		.567
LEFT UPPER	12.4		.891
LEFT LOWER	15.3		1.097
LEFT BASE	12.6		1.188

	45.9		

104174. PERFUSION WASH-OUT	V.	T1/2	K/T1/2	V./V	V./Q.
RIGHT APEX	13.3	38.0	.00295	1.189	1.429
RIGHT UPPER	12.0	54.0	.00266	.837	.943
RIGHT LOWER	16.0	42.0	.00355	1.076	.897
RIGHT BASE	13.3	38.0	.00295	1.189	.940

	54.7				
LEFT APEX	5.6	80.0	.00123	.565	.996
LEFT UPPER	12.0	52.0	.00266	.869	.975
LEFT LOWER	14.4	44.0	.00318	1.027	.936
LEFT BASE	13.3	36.0	.00294	1.255	1.056
	------		------		
	45.3		.02213		

TYPE OF CURVE *

104176.					
SINGLE BREATH	V.			V./V	V./Q.
RIGHT APEX	10.2			.910	1.094
RIGHT UPPER	14.1			.981	1.106
RIGHT LOWER	16.0			1.072	.894
RIGHT BASE	14.5			1.288	1.018

	54.7				
LEFT APEX	7.5			.762	1.344
LEFT UPPER	12.3			.890	.998
LEFT LOWER	12.9			.923	.841
LEFT BASE	12.5			1.182	.995

	45.3				

104178.					
SINGLE BREATH	V.			V./V	V./Q.
RIGHT APEX	8.8			.787	.946
RIGHT UPPER	13.6			.948	1.069
RIGHT LOWER	15.0			1.007	.840
RIGHT BASE	13.1			1.165	.921

	50.5				
LEFT APEX	9.9			1.004	1.770
LEFT UPPER	12.5			.905	1.016
LEFT LOWER	14.1			1.011	.921
LEFT BASE	12.9			1.217	1.024

	49.5				

104180.					
SINGLE BREATH	V.			V./V	V./Q.
RIGHT APEX	11.5			1.026	1.234
RIGHT UPPER	12.2			.853	.962
RIGHT LOWER	14.0			.936	.781
RIGHT BASE	14.3			1.277	1.010

	52.1				
LEFT APEX	9.0			.913	1.610
LEFT UPPER	11.8			.852	.956
LEFT LOWER	13.7			.978	.892
LEFT BASE	13.5			1.270	1.069

	47.9				

UNIVERSITY OF ALBERTA HOSPITAL

XENON-133 REGIONAL PULMONARY FUNCTION REPORT

TYPE OF CURVE *

104182. WASH-IN	K	T1/2	K/T1/2	V./V	V./Q.	V.
RIGHT APEX	11.2	34.0	.00330	.787	.946	8.8
RIGHT UPPER	14.3	28.0	.00512	.955	1.077	13.7
RIGHT LOWER	14.9	24.0	.00621	1.115	.930	16.6
RIGHT BASE	11.2	22.0	.00510	1.216	.962	13.6
	------					-----
	51.7					52.3
LEFT APEX	9.9	34.0	.00290	.787	1.388	7.8
LEFT UPPER	13.9	28.0	.00495	.955	1.072	13.2
LEFT LOWER	14.0	26.0	.00538	1.029	.938	14.4
LEFT BASE	10.6	24.0	.00442	1.115	.938	11.8
	------		------			-----
	48.3		.03738			47.2

104184. WASH-OUT	V.	T1/2	K/T1/2	V./V	V./Q.
RIGHT APEX	10.2	38.0	.00295	.912	1.097
RIGHT UPPER	12.4	40.0	.00359	.867	.977
RIGHT LOWER	15.2	34.0	.00439	1.019	.850
RIGHT BASE	12.2	32.0	.00351	1.083	.857

	50.0				
LEFT APEX	9.0	38.0	.00259	.912	1.609
LEFT UPPER	13.3	36.0	.00385	.963	1.080
LEFT LOWER	16.2	30.0	.00466	1.155	1.053
LEFT BASE	11.5	32.0	.00331	1.083	.912
	------		------		
	50.0		.02885		

UNIVERSITY OF ALBERTA HOSPITAL

XENON-133 REGIONAL PULMONARY FUNCTION REPORT

TYPE OF CURVE *

AVERAGES	V.			V./V	V./Q.
RIGHT APEX	9.5			.848	1.020
RIGHT UPPER	13.9			.968	1.091
RIGHT LOWER	16.3			1.093	.912
RIGHT BASE	14.0			1.252	.990

	53.8				
LEFT APEX	7.6			.775	1.366
LEFT UPPER	12.8			.923	1.035
LEFT LOWER	13.6			.976	.890
LEFT BASE	12.2			1.148	.966

	46.2				

```
C       MAIN PROGRAM FOR VENTILATION SYSTEM OF PROGRAMS
C
C       LABELLED COMMON AREAS
      COMMON/AREA1/TVOL,TVA,M,N,       TV1,TV2
      COMMON/AREA2/DATA,RES,NPT,NN
      COMMON/AREA3/INCR,INCRM,NAVG,TB,TOP
      COMMON/AREA4/ACTCON,CALFAC
      COMMON/AREA5/POINTS
      REAL   INCR( 23,8),TOP(23,8),   INCRM( 23,8)
      INTEGER*2 POINTS(62,110)
      LOGICAL GLOG
      DIMENSION LPHA(12),CALFAC(8)
      DIMENSION TVOL( 30), DATA( 23,8,200),RES( 23,8),NPT( 23,8)
C       THE BOUNDS FOR THE TABLES ARE
C       8 DETECTOR PAIRS
C       200 DATA POINTS FOR EACH TIME SEQUENCE
C       20 BREATHS
C
C       TB IS THE TIME BASE
C       ACTCON IS THE CONCENTRATION OF RADIOACTIVE GAS IN
C       INSPIRED AIR
C       CALFAC IS THE CALIBRATION FACTOR
C       FRC IS THE FUNCTIONAL RESIDUAL CAPACITY
C       DS IS THE DEAD SPACE VOLUME
C
C       THESE VALUES ARE PICKED UP FROM THE HEADER CARD
C       ICOUNT IS THE COUNTER FOR THE NUMBER OF RUNS OR GROUPS
C       OF DATA BEING PROCESSED
C
      IO=8
      READ(1,104)((POINTS(I,J),I=1,62),J=1,110)
300   WRITE(IO,100)
C       READ AND PRINT      HEADER  CARD
      READ(1,200,END=900)ICOUNT,TB,ACTCON,LPHA ,FRC,DS,GLOG,
     1(CALFAC(I),I=1,8)
      IF( ICOUNT.GE. 99999999) GO TO 900
C       IF ICOUNT EQUAL 99999999 THIS MEANS END OF PROCESSING OF
C       DATA GROUPS
      WRITE (IO,101) ICOUNT,LPHA
      WRITE (IO,103)  TB, ACTCON, (CALFAC(I),I=1,8),FRC,DS
      CALL TIDVOL(IO,FRC,DS)
      CALL INPUT(IO,GLOG)
      CALL AVECUV(IO)
      CALL ANACUV(IO)
      CALL INSIDE(IO)
      CALL OUTSIDE(IO)
      CALL VENT(IO)
      CALL POLFT(IO)
      GO TO 300
900   CONTINUE
      WRITE(IO,102)
      STOP
100   FORMAT(1H1,'VENTILATION SYSTEM OF PROGRAMS'////)
```

```
101   FORMAT(1X,'RUN',I10,10X, 18A4//)
102   FORMAT(1HO,20X,'END OF RUNS ')
103   FORMAT(1H-,'ENTRY PARAMETERS'// 15X,'TIME BASE ',23X,F10.2//
     1  15X, 'CONCENTRATION OF RADIOACTIVE GAS', F10.2//
     2  15X, 'CALIBRATION FACTORS',13X,F10.2/7(47X,F10.2/)/15X,'FUNCTION
     3  AL RESIDUAL CAPACITY',4X,F10.2//15X,'DEAD SPACE VOLUME',15X,F10.2/
     4  /)
104   FORMAT(62A1)
200   FORMAT(I10,2F10,2, 12A4/2F10.0,L1/8F10.0)
      END
```

```
      SUBROUTINE TIDVOL (IO,FRC,DS)
C        SUBROUTINE TO INPUT TIDAL VOLUME VALUES (TVOL)
C        AND TO FIND THEIR AVERAGE  (TVA).
C
C        TV1   AVERAGE TIDAL VOLUME FOR BREATHS 1 TO 10
C        TV2   AVERAGE TIDAL VOLUME FOR BREATHS 11 TO 20
      COMMON /AREA1/ TVOL,TVA,M,N,TV1,TV2
      DIMENSION TVOL(30), TEMP(30)
C        NOW INPUT TVOL VALUES
C        AND CALCULATE THE NUMBER OF BREATHS (N)
C        BY COUNTING INPUT VALUES UNTIL A ZERO OR BLANK
C        IS ENCOUNTERED
      N=0
      M2=0
1     CONTINUE
      M1=M2+1
      M2=M2+8
      READ (1,9) (TVOL(J),J=M1,M2
      DO 2 J=M1,M2
      IF (TVOL (J).GT.0.001) N=N+1
2     CONTINUE
      IF (M2.GE.20) GO TO 3
      IF (TVOL(M2).GT.0.001) GO TO 1
3     IF (N.GT.20) N=20
C        FIND AVERAGE TIDAL VOLUME   (TVA)
      TVA=0
      DO 4 L=1,N
4     TVA=TVA+TVOL(L)
      XN=N
      TVA=TVA/XN
      CALL DEAD (FRC,DS,LO,TEMP)
C        OUTPUT TIDAL VOLUME VALUES
      WRITE (IO,11)
      WRITE (IO.12) (J,TVOL(J),TEMP(J),J=1,N
C        COMPUTE AND PRINT AVERAGES
      TVA=0
      DO 5 1=1,N
      TVOL(L)=TEMP(L)
5     TVA=TVA+TVOL(L)
      TVA=TVA/XN
      WRITE (IO,10) N,TVA
      TV1=0
      TV2=0
      IF (N.LT.10) GO TO 8
      DO 6 L=1,10
6     TV1=TV1+TVOL(L)
      TV1=TV1/10
      L1=1
      L2=10
      WRITE (IO,13) L1,L2,TV1
      IF (N.LT.20) GO TO 8
      DO 7 L=11,20
7     TV2=TV2+TVOL(L)
      L1=11
      L2=20
```

```
      TV2=TV2/10
      WRITE (IO,13) L1,L2,TV2
8     CONTINUE
      RETURN
C
9     FORMAT (8F10.2)
10    FORMAT (//1X,'NUMBER OF BREATHS',2X,I10,10X,'AVERAGE TIDAL VOLUME'
     1,2XF10.2//)
11    FORMAT ('1TIDAL VOLUME VALUES'/'-',10X,'BREATH',10X,'TIDAL VOLUME'
     1,5X'CORRECTED VOLUME'/)
12    FORMAT ('0',12X,13,11XF11.2,10X,F10.2)
13    FORMAT (1X,I2,' TO ',I2,10X,'AVERAGE TIDAL VOLUME'2X,F10.2/)
      END
```

```
      SUBROUTINE DEAD (FRC,DS,IO,TEMP)
C
C        SUBROUTINE TO CORRECT FOR DEAD SPACE
      COMMON /AREA1/TVOL,TVA,M.N.TV1,TV2
      TEMP(1)=TVOL(1)-DS
      DO 2 I=2,N
      S=0
      IX=0
1     S=S+((FRC+DS)/(FRC+TVA)**IX
      IX=IX+1
      IF (IX.LE.(I-2)) GO TO 1
2     TEMP(I) =TVOL(I)-DS+S*(TVA-DS)/(FRC+TVA)
      RETURN
      END
```

```
      SUBROUTINE INPUT(IO,GLOG)
C        SUBROUTINE TO INPUT DATA POINTS OF ANALYSER FROM TAPE,
C        DEFINE RESIDUALAREAS,
C        NORMALIZE DATA TO STANDARD TIDAL VOLUME
C
      COMMON/AREA1/TVOL,TVA,M.N,     TV1,TV2
      COMMON/AREA2/DATA,RES,NPT,NN
C
C        WHEN 'GLOG' IS TRUE, GRAPHS OF RAW DATA ARE PRINTED
      LOGICAL GLOG
      INTEGER TAGWD1,TAGWD2,LIST(3)/2,215,218/,POINTS(2,100)
C
C        IN THE EVENT OF TAPE READ ERROR, BRANCH TO 299
      CALL GETIHC(IERR,LIST,&299)
      READ(1,106)TAGWD1,TAGWD2
      DIMENSION TVOL(30),OUT(200),SMOOTH(200)
      DIMENSION DATA(23,8,200),RES(23,8),NPT(23,8)
      LINE=6
      DO 600 K=1,8
      DO 600 L=1,23
600   NPT(L,K)=0
C        INPUT DATA POINTS FROM TAPE
C        ONE TAPE RECORD CONTAINS 1601 PIECES OF INFORMATION
206   IN=1
C        ASSUME CHANNELS GO FROM 1 TO 200
205   READ(2,105,ERR=299,END=300)ITAG,((DATA(IN,ID,I),I=1,200),ID=1,8
      IF(ITAG.LT.TAGWD1)GO TO 205
      IF(ITAG.GT.TAGWD2)GO TO 300
      IF(.NOT.GLOG)WRITE(IO,108)
      IF(LINE.LT.6)GO TO 211
      IF(.NOT.GLOG)WRITE(IO,101)
      LINE=0
211   LINE=LINE+1
      DO  200   ID=1,8
      RES(IN,ID)=0.0
C        FIND LAST CHANNEL WITH MEANINGFUL DATA, CALL  NPT
      K=200
202   IF(DATA(IN,ID,K).GT.0.0)GO TO 201
      IF(K.EQ.2) GO TO 200
      K=K-1
      GO TO 202
201   CONTINUE
      K=K-1
      NPT(IN,ID) = K
C
C        SMOOTHING PROCEDURE
      DO 250 KK=1,K
      IF(KK.GT.100)GO TO 250
      POINTS(1,KK)=DATA(IN,ID,KK)
250   SMOOTH(KK)=DATA(IN,ID,KK)
      CALL SE15(SMOOTH,OUT,K,IER)
      DO 251 KK=1,K
      IF(KK.GT.100)GO TO 251
      POINTS(2,KK)=OUT(KK)
```

```
251   DATA(IN,ID,KK)=OUT(KK)
      DO 252 I=1,5
252   RES(IN,ID)=RES(IN,ID)+DATA(IN,ID,L)
      RES(IN,ID)=RES(IN,ID)/5.0
      IF(GLOG)WRITE(LO,101)
      WRITE(LO,102)IN,ID,K,DATA(IN,ID,K),RES(IN,ID)
C
C        NORMALIZE DATA POINTS TO STANDARD TIDAL VOLUME
C        SUBTRACT RESIDUAL AREA FROM DATA POINTS
      DO 204 L=1,K
      DATA(IN,ID,L)=  DATA(IN,ID,L)- RES(IN,ID)
      DATA(IN,ID,L)= (DATA(IN,ID,L)/ TVOL(IN)) * TVA
204   CONTINUE
C        NORMALIZE RESIDUALS
      RES(1+IN,ID)=(RES(1+IN,ID)/TVOL(IN)*TVA
      IF(GLOG)CALL PICT(POINTS,K,.TRUE.)
200   CONTINUE
      IN = IN+1
      IF ( IN.GT. N )  GO TO 300
      GO TO 205
299   WRITE(IO,109)IN
300   CONTINUE
      IN=IN-1
      IF(IN.EQ.0)GO TO 206
      IF (N.NE. IN)  WRITE (IO,100)N,IN
      IF(IN.LT.N)N=IN
      NN=N
      RETURN
100   FORMAT(1HO,'ERROR IN BREATH COUNTS' 1X,
     1 'TIDAL VOLUME',I5,10X,'ANALYSER', I5)
101   FORMAT(//1H1,'DATA FROM ANALYSER'// 6X,'BREATH',2X,'DETECTOR',4X,
     1 'END-PT',5X,'VALUE AT END-PT',12X,'RESIDUAL')
102   FORMAT(2X, 3I10,2F20.2)
105   FORMAT(I6,8(200F3.0))
106   FORMAT(I6,I7)
107   FORMAT(1X,I5)
108   FORMAT( ' ')
109   FORMAT(' TAPE ERROR IN BREATH',I3)
      END
```

```
      SUBROUTINE AVECUV (IO)
C        SUBROUTINE TO CONSTRUCT THE 3 SETS OF AVERAGE CURVES
      COMMON /AREA2/ DATA,RES,NPT,N
      DIMENSION DATA(23,8,200),RES(23,8),NPT(23,8)
      NAVG=N+1
      N1=NAVG+1
      N2=NAVG+2
      DO 4 J=1,8
      NPT(NAVG,J)=0
      DO 1 II=1,N
      NPT(NAVG,J)=NPT(NAVG,J)+NPT(II,J)
      IF (II.EQ.20) NPT(N2,J)=NPT(NAVG,J)-NPT(N1,J)
      IF (II.EQ.10) NPT(N1,J)=NPT(NAVG,J)
1     CONTINUE
      IF (N.NE.20)GO TO 2
      NPT(N2,J)=NPT(N2,J)/10
2     IF (N.LT.10) GO TO 3
      NPT(N1,J)=NPT(N1,J)/10
3     CONTINUE
      NPT(NAVG,J)=NPT(NAVG,J)/N
      DO 4 K=1,200
      DATA (NAVG,J,K)=0
      DO 4 I=1,N
      DATA(NAVG,J.K)=DATA(NAVG,J,K)+DATA(I,J,K)
4     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE ANACUV (IO)
C
C        SUBROUTINE TO DO A CURVE ANALYSIS FOR EACH OF (N+1) SETS
      COMMON /AREA2/DATA,RES,NPT,N
      COMMON /AREA3/INCR,INCRM,NAVG,TB,TOP
      DIMENSION DATA(23,8,200),RES(23,8),NPT(23,8)
      REAL INCR(23,8),TOP(23,8),INCRM(23,8)
      LOGICAL LOGG,KW10,KW20
      KW10=.FALSE.
      KW20=/FALSE
      DO 1 K=1,8
      DO 1 KK=1,23
      INCR(KK)=0
1     CONTINUE
      NN=N+1
      NAVG=NN
      LINE =5
      IF (N.GE.10) KW10=.TRUE.
      IF (N.GE.20) KW20=.TRUE.
      IF (KW20) NN=NN+2
      IF (KW10.AND.(.NOT.KW20)) NN=NN+1
      DO 11 J=1,NN
      IF (LINE.LT.5) GO TO 2
      WRITE (IO.12)
      LINE =0
2     LINE=LINE+1
      LOGG=J.EQ.NAVG
      IF (LOGG) WRITE (IO,15)
      IF (J.EQ.(NAVG+1)) WRITE (IO,16)
      IF (J.EQ.(NAVG+2)) WRITE (IO,17)
      IF (J.LT.NAVG) WRITE (IO,14)J
      DO 11 K=1,8
      XL=0
      MPT=NPT(J,K)
      XMAX=0
      DO 3 L=1,MPT
C        MAXIMUM HEIGHT
      IF (DATA(J.K,L).GT.XMAX) XL=L
      IF (DATA(J,K,L).GT.XMAX) XMAX=DATA(J,K,L)
3     CONTINUE
      TOP(J,K)=XMAX
C        TIME TO MAXIMUM HEIGHT
      TMAX=XL*TB
C        RISE  TIME
      LX=XL
      I10=1
      X90=0.90*XMAX
      X10=0.10*XMAX
      DO 4 L=1,LX
      IF (DATA(J,K,L).GE.X10) I10=L
      IF (DATA(J,K,L).GE.X10) GO TO 5
4     CONTINUE
5     CONTINUE
      DO 6 L=I10,LX
      IF (DATA(J,K,L).GE.X90) I90=L
```

```
      IF (DATA(J,K,L).GE.X90) GO TO 7
6     CONTINUE
7     CONTINUE
      RTIME=(I90-I10)*TB
C        DURATION
      DUR=TB*NPT(J,K)
C        PLATEAU TIME -
C        SEARCH CHANNELS FROM POSITIONS XL TO 200
C        TO FIND ONE THE SAME HEIGHT AS THE CHANNEL
C        AT LOCATION I90.
      DO 8 L=LX,200
      IF (DATA(J,K,L).LE.DATA(J,K,I90)) GO TO 9
8     CONTINUE
      L=200
9     PTIME+(L-I90)*TB
      DO 10 L=1,MPT
C        FIND INTEGRAL  INCR, AREA FROM 0 TO NPT(J,K)
      IF (DATA(J,K,L).GT.0.0) INCR(J,K)=INCR(J,K)+DATA(J,K,L)
C        FIND INTEGRAL INCRM,AREA FROM 0 TO TMAX
      IF (L.EQ.LX) INCRM(J,K)= INCR(J,K)*NPT(NAVG,K)/NPT(J,K)
10    CONTINUE
      INCR(J,K)=INCR(J,K)*NPT(NAVG.K)/NPT(J,K)
      WRITE (IO,13) K,XMAX,TMAX,RTIME,DUR,PTIME,INCRM(J,K),INC R(J,K)
11    CONTINUE
      RETURN
C
12    FORMAT (1H1,'CURVE ANALYSIS REPORT'//9X,'MAX HEIGHT',7X,'TIME TO M
     1AX',9X,'RISE TIME',10X,'DURATION',6X'PLATEAU TIME",13X,'INCRM',14
     2X,'INCR'/)
13    FORMAT (1X,'DET',I2,1X,F12.2,6F18.2)
14    FORMAT (1HO,'BREATH',I5)
15    FORMAT (1HO,'AVERAGE BREATH')
16    FORMAT (1Ho,'BREATHS 1 TO 10')
17    FORMAT (1HO,'BREATHS 11 TO 20)
      END
```

```
      SUBROUTINE INSIDE(IO)
C        INSIDE OR ENSET RATIOS
C        COMPARE INCR VALUES WITHIN  EACH SET OF 8 FOR
C        (N+1)NUMBER OF CASES.
C        FIRST NORMALIZE WITHIN EACH SET BY SETTING
C        MAX INCR VALUE TO 100, AND CORRESPONDINGLY
C        ALTERING OTHER 7 MEMBERS OF THE SET.
C
C        PERFORM IDENTICAL PROCEDURE FOR INCRM & TOP
C
C        NEXT COMPARE RESULTS FOR INCR AND INCRM
C
      COMMON /AREA3/INCRM,NAVG,TB,TOP
      DIMENSION LAP(3)
      DATA LAP    /'NCR', 'NCRM', 'MAX' /
      REAL     LL(3), TEMP(23,3)
      LOGICAL TEST
      REAL   INCR(23,8), TOP(23,8),  INCRM( 23,8)
      REAL     RATIO(8,3), RR(3), T(3)
      LINE=3
      NK=NAVG
      IF((NAVG-1).GE.10)NK=NAVG+1
      IF((NAVG-1).GE.20)NK=VAVG+2

      DO  300   J=1,NK
      IF(LINE.LT.3) GO TO 211
      LINE=0
      WRITE(IO,101)
211   LINE=LINE+1
      XMAX1=0
      XMAX2=0
      XMAX3=0
      DO   301  L=1,8
      IF (INCR(J,L).GT.XMAX1 )  XMAX1= INCR(J,L)
      IF(INCRM(J,L).GT.XMAX2 )  XMAX2=INCRM(J,L)
      IF(TOP(J,L).GT.XMAX3)XMAX3=TOP(J,L)
301   CONTINUE
      DO 401 L=1,3
      LL(L)=0
      RR(L)=0
401   CONTINUE
C        SET UP NEW VALUES FOR 'J' SET OF INCR AND INCRM
         VALUES, DEPENDING ON XMAX1 AND XMAX2.
C
      DO    302  L=1,8
      RATIO(L,1)=(100.*INCR(J,L))/ XMAX1
      RATIO(L,2)=(100.*INCRM(J,L))/XMAX2
      RATIO(L,3)=(100.*TOP(J,L))/  XMAX3
      TEST= (1.LE.4)
      DO    402  K=1,3
      IF(TEST)LL(K)=LL(K)+RATIO(L,K)
      IF(.NOT.TEST) RR(K)=RR(K) + RATIO(L,K)
402   CONTINUE
302   CONTINUE
      DO  403   K=1,3
403   T(K)= LL(K) + RR(K)
```

```
      DO   405  KN=1,3
      DO   405  L=1,8
405   TEMP(L,KN)=100.*RATIO(L,KN)/ T(KN)
      NL=8
      DO   407 KN=1,3
      DO   407  L=1,4
      TEMP(NL+L,KN)=100.*RATIO(L,KN)/  LL(KN)
407   CONTINUE
      DO 408  KN=1,3
      DO 408   L = 5,8
      TEMP(NL+L,KN)=100.*RATIO(L,KN)/RR(KN)
408   CONTINUE
      DO 409  KN=1,3
      TEMP(17,KN) = (LL(KN)*100.) / T(KN)
      TEMP(18.KN)=  (RR(KN)*100)/  T(KN)
      TEMP(19,KN)= LL(KN)/ RR(KN)
409   CONTINUE
      IF ( J.EQ. NAVG.)WRITE (IO,1023)
      IF(J.EQ.(NAVG+1))WRITE (IO,1024)
      IF(J.EQ.(NAVG+2)WRITE(IO,  1025)
      IF ( J.LT.NAVG) WRITE(IO,1022) J
      WRITE(IO,102)  (LAP(KN),(TEMP(L,KN),L=1,8),KN=1,3),
     1(LAP(KN),(TEMP(L,KN),L=9,12),KN=1,3),(LAP(KN),(TEMP(L,KN),
     2  L=13,16),KN=1,3)
     3(LAP(KN),(TEMP(L,KN),L=17,19),KN=1,3 )
300   CONTINUE
      RETURN
101   FORMAT(1H1,6X,'INSIDE RATIOS'/1HO. 7X,'AREA 1',4X,'AREA 2',4X
     1'AREA3',4X,'AREA 4',4X,'AREA 5',4X,'AREA 6',4X,'AREA 7',4X,
     2'AREA 8')
102   FORMAT              (1X,12(1H-)/3(1X,1HI,A4,1X,8(F6.2,4X),10X,
     1 'AREA/TOTAL'/),1H /3(1X,1HI,A4,1X,    4(F6.2,4X),50X.
     2'AREA/TOTAL 1-4/),1H/3(1X,1HI,A4,41X,4(F6.2,4X),10X.
     3'AREA/TOTAL 5-8'/),1H,6X,'TOTAL 1-4/TOTAL',20X,''TOTAL 5-8/TOTAL'
     4,20X,'TOTAL 1-4/TOTAL 5-8'/  3(1X,1HI,A4,1X, F15.3,20X,
     5 F15.3,20X                    F19.3/))
1022  FORMAT(1HO,'BREATH',I6)
1023  FORMAT(1HO,'AVERAGE BREATH')
1024  FORMAT(1HO,'BREATHS 1 TO 10')
1025  FORMAT(1HO,'BREATHS 11 TO 20')
      END
```

```
      SUBROUTINE OUTSIDE(IO)
C
C        SUBROUTINE TO COMPARE OUTSIDE RATIOS
C        FOR EACH DETECTOR COMPARE THE INCR VALUES FOR (N+1)
C        NUMBER OF CASES.
C        FIRST NORMALIZE BY SETTING MAX INCR VALUE TO 100,
C        AND CORRESPONDINGLY CHANGING THE OTHER 'N' MEMBERS
C
      COMMON/AREA3/INCR,INCRM,NAVG,TB,TOP
      REAL  INCR( 23,8),MAXR(23,8), INCRM( 23,8),RATIO( 23)
      DIMENSION KDUM(23)
      WRITE(IO,101)
      N=NAVG-1
      DO          500  K=1,N
500   KDUM(K)=K
      WRITE(IO,103)  ( KDUM(K),K=1,N)
      WRITE(IO,105)
C        LARGEST INCR VALUE STORED IN XMAX
      DO   300      J=1,8
      XMAX=0.
      XMAX1=0.
      DO    301     K=1,NAVG
      IF (INCR(K,J) .GT. XMAX)  XMAX=INCR(K,J)
      IF(TOP(K,J).GT.XMAX1)XMAX1=TOP(K,J)
301   CONTINUE
C        FIRST NORMALIZE (N+1)VALUE
      RATIO (NAVG) = INCR(NAVG,J) *100/ XMAX
      MAXR(NAVG,J)=TCP(NAVG,J)*100./XMAX1
C        NORMALIZE REMAINING N VALUES AND
C        CALCULATE OUTSIDE RATIOS
      DO 302  K=1,N
      RATIO(K) = INCR(K,J) *100/ XMAX
      RATIO(K)= RATIO(K) *100 / RATIO(NAVG)
      MAXR(K,J)=(TOP(K,J)*100./XMAX1)*100./MAXR(NAVG,J)
302   CONTINUE
      WRITE (IO,102)  J,    (RATIO(K),K=1,N)
300   CONTINUE
      WRITE(IO,104)
      WRITE(IO,103)(KDUM(K),K=1,N)
      WRITE(IO,105)
      DO 400 J=1,8
400   WRITE(IO,102)J,(MAXR(K,J),K=1,N)
      RETURN
101   FORMAT(1H1,'OUTSIDE RATIOS (INCR)'//30X,'BREATH NUMBERS')
102   FORMAT("0",I2,10X,10F11.2/'0',12X10F11.2)
103   FORMAT(11X,10I11)
104   FORMAT(1H1,'OUTSIDE RATIOS (MAX)'//30X,'BREATH NUMBERS')
105   FORMAT(2X, 'DETECTOR')
      END
```

```
      SUBROUTINE VENT(IO)
C        USE AVERAGE INCR VALUES (N+1) SET, AND
C        DIVIDE BY ACTCON AND CALFAC TO ARRIVE AT
C        THE VENTILATION AT A PARTICULAR DETECTOR
      WRITE(IO,101)
      WRITE(IO,102)
      COMMON/AREA1/ TVOL, TVA,M,N ,                TV1,TV2
      COMMON/AREA3/INCR,INCRM,NAVG,TB,TOP
      COMMON/AREA4/ACTCON,CALFAC
      DIMENSION TVOL ( 30), OUT(8,2),CALFAC(8)
      INTEGER*2 GRAPH (55,122), XAXIS(8), KAR(8)
      DATA KAR/'1','2','3','4','5','6','7','8'/
      REAL  INCR( 23,8),TOP(23,8), INCRM ( 23,8)
      SUM=0
      DO  300   J+1,8
      OUT(J,1) = INCR(NAVG,J)/ (ACTCON *CALFAC(J))
      OUT(J,2) = OUT(J,1)* 100.0/ TVA
      SUM=SUM+  OUT (J,1)
300   CONTINUE
      FUDGE=SUM/TVA
      DO 350 J=1,8
      OUT(J,1)=OUT(J,1)/FUDGE
      OUT(J,2)+OUT(J,2)/FUDGE
350   WRITE(IO,103)J,OUT(J,1),OUT(J,2
      SUM=SUM/FUDGE
      WRITE(IO,104)  SUM
      WRITE(IO,107)FUDGE
C        DIAGRAM OF LUNGS
      CALL LUNG(GRAPH)
      READ(1,201) (XAXIS(J),YAXIS(J),J=1,8)
      WRITE(IO,204)(XAXIS(J),YAXIS(J),J=1,8
      DO  301 J=1,8
      IF ( XAXIS(J) .GT.60)  XAXIS(J)= XAXIS(J)+2
      GRAPH( XAXIS(J) , XAXIS(J)=KAR(J)
301   CONTINUE
      WRITE(IO,105)  ((GRAPH(J,K),K=1,122 ) ,J=1,55
      RETURN
101   FORMAT(1H1,20X,'VENTILATION REPORT')
102   FORMAT('0','REGION",5X,'TRUE VOLUME(ML.)'5X,'DIVIDE BY TVA'//)
103   FORMAT(1X.  I5,6X,  F15.2,6X,F12.2
104   FORMAT(1HO,14X,12(1H-)/1X,'TIDAL VOLUME',2X,F12.2//)
105   FORMAT(4X,122A1)
106   FORMAT(1H1,57X,'DIAGRAM OF LUNGS'/)
107   FORMAT('-RATIO OF PATIENT VENTILATION TO NORMAL VENTILATION',
     1F11.4)
201   FORMAT(1615)
202   FORMAT(8A1)
203   FORMAT(1X,8(1X,A1)
204   FORMAT('-',10X,'COORDINATES OF DETECTOR', 8(214,2X))
      END
```

```
      SUBROUTINE LUNG (GRAPH)
C
C        THIS SUBROUTINE DRAWS A DIAGRAM OF THE LUNGS SHOWING THE
C        LOCATIONS OF THE 8 DETECTOR PAIRS.
      COMMON/ AREA5/ POINTS
      DO 1 L=1,55
      DO 1 J=1,62
1     GRAPH(L,J)=POINTS(J,L)
      DO 2 L=1,55
      DO 2 J=1,60
2     GRAPH(L,J+62)=POINTS(J,L+55)
      RETURN
      END
```

```
      SUBROUTINE POLFT(IO)
C
C        THIS SUBROUTINE SETS UP A TABLE OF LOGARITHMIC VALUES TO BE
C        USED BY THE SUBROUTINE 'PLOTS'.
      COMMON/PTS/X
      COMMON/AREA2/DATA,RES,NPT,NN
      COMMON/AREA3/INCR,INCRM,NAVG,TB,TOP
      REAL INCR(23,8),TOP(23,8),INCRM(23,8)
      DIMENSION DATA(23,8,200),RES(23,8),NPT(23,8),X(23,2)
      N=NN-1
C        CALCULATE POINTS FOR 'PLOTS AND CORRELATION'
      DO 200 K=1,8
      WRITE(IO,300) K
      DO 201 J=1,N
      X(J,1)=J
      X(J,2)= RES(J+1,K) -  RES(J,K)
      IF(X(J,2).LE.0.0)X(J,2)=1.0
      X(J,2)=ALOG(X(J,2))
      WRITE(IO,301) X(J,1),X(J,2)
201   CONTINUE
      CALL PLOTS (N,2,IO)
200   CONTINUE
      RETURN
300   FORMAT(1H1,'PLOT OF LOG(RESIDUAL (N) -RESIDUAL (N-1))'/
     1  1X,'DETECTOR',I10// 18X,'POINTS')
301   FORMAT(1X,2F20.2)
      END
```

```
      SUBROUTINE PLOTS(NUMOBS,NVAR,IO)
C
C        PROGRAM FOR PLOTS AND CORRELATIONS
      DIMENSION X(23,2)
      REAL S(2,2),SUM(2),XMIN(2), XMAX(2), Y(150)
      COMMON/PTS/ X
      NROWS=1500/NVAR
      CALL CORREL(NVAR,NROWS,S,SUM,XMIN,XMAX, Y,A,B,  NUMOBS,
     1 IX,J,NUMVAR,IO
      NOB=(ALOG(0.05*EXP(A))-A)/ B
      WRITE(IO,100)NOB
      RETURN
100   FORMAT('-THE NUMBER OF BREATHS REQUIRED TO REACH 95% EQUILIBRIUM
     1IN THIS AREA IS:',I6)
      END
```

```
      SUBROUTINE CORREL(NVAR,NROWS,S,SUM,XMIN,XMAX,  Y,A,B, NUMOBS
     1  IX,J,NUMVAR,IO)
      REAL S(NVAR,NVAR),SUM(NVAR),     XMIN(NVAR),XMAX(NVAR),
     1   Y(150),                                  DOTV(120),SMIN(2),
     2SMAX(2)
      LOGICAL*1 RSMIN( 2)
      INTEGER*2 M(50,100)
      DATA DOT/1H./
      DATA PLUS/1H+/
      DIMENSTION  X(23,2)
      COMMON/PTS/X
      DO 1001  I=1,120
1001  DOTV(I)=DOT
4     CONTINUE
      IX=1
C        INITIALIZATION OF WORK  MATRICES
      DO 403 I=1,NVAR
      SUM(I)=0
      XMIN(I)=0.0
      XMAX(I)=-1.E75
      RSMIN(I)=.FALSE.
      RSMAX(I)=.FALSE.
      DO  403  J=1,NVAR
403   S(I,J)=0
407   NOBS=NUMOBS
      NBLOKS=0
5     NBLOKS=NBLOKS+1
C        COMPUTATION OF SUMS,PRODUCTS, MINIMA AND MAXIMA
      NUMLST=NUMOBS
12    DO 13 K=1,NUMLST
      DO 13 J=1,NVAR
      SUM(J)=SUM(J)+X(K,J)
      XMIN(J)=AMIN1(XMIN(J),X(K,J))
      XMAX(J)=AMAX1(XMAX(J),X(K,J))
      DO 13 I=J,NVAR
13    S(I,J)=S(I,J)+X(K,I)*X(K,J)
16    CONTINUE
      LINES=60
      FN+NOBS
      FNM1=NOBS-1
      NVARM1=NVAR-1
      DO  18  J=1,NVAR
      DO  17  I=J,NVAR
C        COMPUTATION OF COVARIANCES
      S(I,J)+(S(I,J)-(SUM(I)*SUM(J))/FN)/FNM1
C        COMPUTATION OF STANDARD DEVIATIONS
17    IF(I.EQ.J)S(I,J)=SQRT(S(I,J))
C        COMPUTATION OF MEANS
      SUM(J)=SUM(J)/FN
      IF(LINES.LT.60)GO TO 1705
      WRITE(IO,100)
      LINES=4
1705  LINES=LINES+2
      WRITE(IO,101)J,                  SUM(J),S(J,J),XMIN(J),XMAX(J)
      IF(RSMIN(J))XMIN(J)=SMIN(J)
```

```
18    IF(RSMAX(J))XMAX(J)=SMAX(J)
      DO 20 I=1,NVARM1
      IP1=I+1
C        COMPUTATION OF CORRELATION COEFFICIENTS
      DO 19 J=IP1,NVAR
19    S(I,J)=S(J,I)/(S(I,I)*S(J,J))
20    CONTINUE
C        OUTPUT OF CORRELATION COEFFICIENTS
      IJ=2
      DO 22 L1=1,NVARM1,18
      LIM=LL+17
      L2=MINO(LIM,NVARM1)
      LINES=60
      DO 21 J=IJ,NVAR
      IF(LINES.LT.60)GO TO 205
      WRITE(IO,104)NOBS
      WRITE(IO,102)(I,I=L1,L2)
      LINES=6
205   JM1=J-1
      L2= MINO(JM1,LIM)
      LINES=LINES+2
21    WRITE(IO,103)J,(S(I,J),I=L1,L2)
22    IJ=IJ+18
C        READ-IN OF SPLOT AND/OR REGRES CARDS
C        SET UP VARIABLES FOR GRAPH
      JY=2
      JX=1
      YRANGE=XMAX(JY)-XMIN(JY)
      XRANGE=XMAX(JX)-XMIN(JX)
C        PICK PROPER SUBSCRIPTS FOR CORRELATION COEFFICIENT
      I=MINO(JX,JY)
      J=MAXO(JX,JY)
      R=S(I,J)
C        COMPUTATION OF LINEAR REGRESSION COEFFICIENT, CONSTANT AND T -VALUE
      B=(R*S(JY,JY))/S(JX,JX)
      A=SUM(JY)-B*SUM(JX)
      DENOM=1.-R*R
      T=1.E38
      IF(DENOM.NE.0.)T=R*SQRT((FN-2.)/DENOM)
C        THIS PIECE READS THE BINARY DATA, PIGEON-HOLES IT, AND FIXES IT UP
2255  NUMOFF=0
      DO 23 I=1,50
      DO 23 J=1,100
23    M(I,J)=0
      NUMPTS=NROWS
      DO 24 INDEX=1,NBLOKS
      IF(INDEX.EQ.NBLOKS)NUMPTS=NUMLST
      DO 24 K=1,NUMPTS
      I=IFIX(49.99*(X(K,JY)-XMIN(JY))/YRANGE)+1
      IF(I.LE.0.OR.I.GT.50)GO TO 2305
      J=IFIX(99.99*(X(K,JX)-XMIN(JX))/XRANGE)+1
      IF(J.LE.0.OR.J.GT.100)GO TO 2305
      M(I,J)=M(I,J)+1
      GO TO 24
2305  NUMOFF=NUMOFF+1
```

```
24    CONTINUE
      CALL FIXUP(M)
      X1=XMIN(JX)-XRANGE/200.
      X2=XMAX(JX)=XRANGE/200.
      Y1=XMIN(JY)-YRANGE/100.
      Y2=XMAX(JY)+YRANGE/100.
      IF(B.EQ.).)GO TO 26
      XX=(Y2-A)/B
      J=IFIX(99.99*(XX-XMIN(JX))/XRANGE+1.)
      J=J+1
      IF(J.LT.1.OR.J.GT.102)GO TO 26
      DOTV(J)=PLUS
C        PRINT GRAPH
26    WRITE(IO,114)        (DOTV(K),K=1.102)
      IF(J.GE.1.AND.J.LE.102)DOTV(J)=DOT
      YY=A+B*X1
      I1=IFIX(49.99*(YY-XMIN(JY))/YRANGE+1.
      IF(I1.LT.1.OR.I1.GT.50)GO TO 2605
      DOTV(I1)=PLUS
2605  YY=A+B*X2
      I2=IFIX(49.99*(YY-XMIN(JY))/YRANGE+1.)
      I2=I2+50
      IF(I2.LT.51.OR.I2.GT.100)GO TO 2615
      DOTV(I2)=PLUS
2615  WRITE(IO,115)XMAX(JY),DOTV(50),(M(50,J),J=1,100),DOTV(100)
      DO 27 I=1,27
      IF=50-I
27    WRITE(IO,116)DOTV(IK),(M(IK,J),J=1,100),DOTV(IK+50
      WRITE(IO,125)JY,DOTV(22),(M(22,J),J=1,100),DOTV(72)
      WRITE(IO,119)          DOTV(21),(M(21,J),J=1,100),DOTV(71)
      L2=38
      DO 28 I=30,L2
      IK=50-I
28    WRITE(IO,116)DOTV(IK),(M(IK,J),J=1,100),DOTV(IK+50
      WRITE(IO,120)DOTV(11),(M(11,J),J=1,100),DOTV(61)
      WRITE(IO,121)A,DOTV(10 ),(M(10,J),J=1,100),DOTV(60)
      WRITE(IO,122)B,DOTV(9),(M(9,J),J=1,100),DOTV(59)
      WRITE(IO,1225)T,DOTV(8),(M(8,J),J=1,100).DOTV(58)
29    WRITE(IO,123)NOBS,DOTV(7),(M(7,J),J=1,100),DOTV(57)
      WRITE(IO,124)R,DOTV(6),(M(6,J),J=1,100),DOTV(56)
      DO 30 I=45,48
      IK=50-I
30    WRITE(IO,116)DOTV(IK),(M(IK,J),J=1,100),DOTV(IK+50)
      WRITE(IO,115)XMIN(JY),DOTV(1),(M(1,J),J=1,100),DOTV(51)
      IF(I1.GE.1.AND.I1.LE.50)DOTV(I1)=DOT
      IF(I2.GE.51.AND.I2.LE.100)DOTV(I2)=DOT
      IF(B.EQ.0.)GO TO 37
      XX=(Y1-A)/B
      J=IFIX(99.99*(XX-XMIN(JX))/XRANGE+1.)
      J=J+1
      IF(J.LT.1.OR.J.GT.102)GO TO 37
      DOTV(J)=PLUS
37    WRITE(IO,117)(DOTV(K),K=1,102)
      IF(J.GE.1.AND.J.LE.102)DOTV(J)=DOT
      WRITE(IO,118)XMIN(JX),JX,                    XMAX(JX)
```

```
      IF(NUMOFF.GT.0)WRITE(IO,126)NUMOFF
45    CONTINUE
998   IX=7
90    FORMAT(A6,18A4)
91    FORMAT(A6,I4,15A2,2(L1,F9.0))
92    FORMAT(A6,I4,I415)
99    FORMAT(1H1,I5)
100   FORMAT(1HO,4X,8HVARIABLE,28X,4HMEAN,5X,9HSTD. DEV.,7X,7HMINIMUM,
     17X,7HMAXIMUM)
101   FORMAT(/,1X,I3,1X,  30X,4G14.6)
102   FORMAT(/,4X,18I7)
103   FORMAT(/,1X,I3,2X,18F7.3)
104   FORMAT(1HO,5X,24HCORRELATION COEFFICIENTS,10X,12HSAMPLE SIZE=,I5)
114   FORMAT(1H1,  29X,102A1)
115   FORMAT(17X,G13.6,102A1)
116   FORMAT(30X,102A1)
117   FORMAT(30X,102A1)
118   FORMAT(23X,G13.6,20X,8HVARIABLE,I3,1X,     50X,G13.6)
119   FORMAT(30X,102A1)
120   FORMAT(2X,24HLINEAR REGRESSION Y=A+BX,4X,102A1)
121   FORMAT(5X,2HA=,G13.6,10X102A1)
122   FORMAT(5X2HB=,G13.6,10A102A1)
1225  FORMAT(5X,2HT=,F6.2,17X102A1)
123   FORMAT(5X,2HN=,I6,17A,102A1)
124   FORMAT(5X,2HR=,F6.3,17X,102A1)
125   FORMAT(1X,8HVARIABLE,I3,18X,102A1)
126   FORMAT(1X,I10,42H POINTS WERE OFF SCALE FOR THE ABOVE PLOT.)
999   RETURN
      END
```

```
      SUBROUTINE PICT  (POINTS,NUM.LOG)
C
C        THIS ROUTINE DRAWS 1 OR 2 GRAPHS ON A SINGLE SET OF AXES
C        DEPENDING ON THE VALUE OF 'LOG'
C        LOG=.TRUE.         2 GRAPHS
C        LOG=.FALSE.        1 GRAPH
C
C        POINTS IS AN ARRAY OF DIMENSION (2,100) CONTAINING THE POINTS
C        TO BE PLOTTED.
C
C        NUM IS THE NUMBER OF POINTS TO PLOT.
C
C        AUTOMATIC 1-2-5 SCALING IS USED FOR THE VERTICAL AXIS.
C        THE HORIZONTAL SCALE IS FIXED AT 100 POINTS.
      INTEGER POINTS(2,100),BLANK,STAR,GRAPH(51,100),CIST,RANG
      INTEGER SCALE(51),ORD(11)
      LOGICAL LOG
      DATA BLANK/' '/,STAR/'*'/PLUS/'+'/
C        INITIALIZE GRAPH TO BLANKS
      DO 1 J=1,51
      SCALE(J)=BLANK
      DO 1 K=1,100
1     GRAPH(J,K)=BLANK
C
C        SCALING
      NN=NUM
      IF (NUM.GT.100) NN=100
      MIN=0
      MAX=50
      ITOP=50
      DO 3 J=1,2
      DO 2 I=1,NN
2     MAX=MAXO(MAX,POINTS(J,I)
      IF (.NOT.LOG) GO TO 4
3     CONTINUE
4     LS=2
5     IF (MAX.LE.ITOP) GO TO 8
      IF (LS.NE.2) GO TO  6
      LS=0
      ITOP=2*ITOP
      GO TO 5
6     IF (LS.EQ.1) GO TO  7
      LS=1
      ITOP=ITOP*2
      GO TO 5
7     ITOP=ITOP*2.5
      GO TO 4
8     MAX=ITOP
      ISC=0
      DO 9 I=1,51,5
      SCALE(I)=ISC
9     ISC=ISC+MAX/10

      RANG=MAX-MIN
```

```
C
C        CREATE POINTS ON GRAPH
      IPLOT=STAR
      DO 11 K=1,2
      DO 10 J=1,NN
      CIST=MAX-POINTS(K,J)
      L=51-(50*CIST)/RANG
      IF (L.EQ.0) GO TO 10
      IF (L.GT.51) GO TO 10
      GRAPH(L,J)=IPLOT
10    CONTINUE
      IF (.NOT.LOG) GO TO 12
      IPLOT=LUS
11    CONTINUE
12    WRITE (8,16)
      K=51
13    WRITE (8,15)  (GRAPH(K,J),J=1,100)
IF    IF (SCALE(K).NE.BLANK) WRITE (8,18)  SCALE(K)
      K=K-1
      IF (K.GT.0) GO TO 13
      WRITE (8,16)
      IORD=0
      DO 14 I=1,11
      ORD(I)=IORD
14    IORD=IORD+10
      WRITE (8,17) (ORD(I),I=1,11)
      RETURN
C
15    FORMAT (10X,'.',100A1,'.')
16    FORMAT (10X,52('.'))
17    FORMAT ('.',11I10)
18    FORMAT ('+',I9)
      END
```

```
      SUBROUTINE FIXUP (M)
      INTEGER*2 M(50,100)
      INTEGER*2 CHAR(10)/'* 2 3 4 5 6 7 8 9 # '/BLANK/'  '/
      DO 3 I=1,50
      DO 2 J=1,100
      IF(M(I,J).GT.0) GO TO 1
      M(I,J)=BLANK
      GO TO 2
1     IF(M(I,J).GT.10)M(I,J)=10
      M(I,J)=CHAR(M(I,J))
2     CONTINUE
3     CONTINUE
      RETURN
      END
```

APPENDIX III

```
C
C     *****CALCULATION OF TIDAL VOLUMES AND MINUTE VENTILATION*****
C
C     THIS PROGRAM MUST RUN IN REAL TIME
C
      PROGRAM TVOL
      DIMENSION DATA(5),IBUF(64Ø)
C
C        INPUT CALIBRATION FACTOR
C
      WRITE(1,2Ø2)
      READ(1,2Ø3)CAL
C
C        INPUT TIME INTERVAL REQUIRED
C
      WRITE(1,2Ø4)
      READ(1,2Ø3)SEC
      NSCTR=IFIX(SEC)
C
C        COLLECT DATA FROM A/D CONVERTER (64 SAMPLES PER SECOND)
C
      CALL INPUT(NSCTR,1,156,Ø,IBUF,ITRK,IDUM)
C
C     LOCATE BASELINE
C
      SUM=Ø.Ø
      CALL EXEC(1,66,IBUF,64Ø,ITRK,Ø)
      DO 4 I=1,8
4     SUM=SUM+FLOAT(IBUF(I))
      XMIN=SUM/Ø.8
C
C        INITIALIZE ALL COUNTERS
C
      JTR=4
      JTRK=1
      K=1
      J=Ø
      TAVG=Ø.Ø
      AVG=Ø.Ø
      IND=Ø
      VENT=Ø.Ø
      ITIME=Ø
      ISEC=1Ø
      IS=1Ø
90    SUM=Ø.Ø
      J=J+8
      IF(J-64Ø)3ØØ,3Ø1,3Ø1
C
C        CALCULATE AVERAGES
C
3Ø1   IF(ISEC-NSCTR+1)3Ø2,35Ø,35Ø
35Ø   AVG=AVG/FLOAT(IND)
```

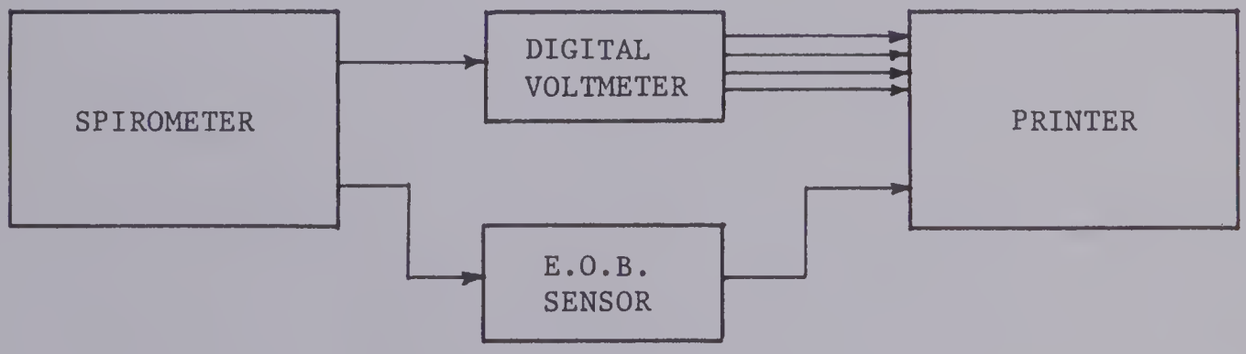
```
      WRITE(6,206)IND,AVG
      TAVG=TAVG/FLOAT(K-1)
      WRITE(6,207)TAVG
      STOP
C
C        INPUT DATA FROM DISC
C
302   CALL EXEC(1,66,IBUF,640,ITRK,IS)
      IS=IS+10
      ISEC=ISEC+10
      J=0
      JTRK=JTRK+1
C
C        INCREMENT TRACKS IF NECESSARY
C
      IF(JTRK,LT.9)GO TO 300
      ITRK=ITRK+1
      JTRK=0
      IS=0
C
C        FIND AVERAGE OF 8 SAMPLES
C
300   DO 5 I=1,8
      KK=I+J
5     SUM=SUM+FLOAT(IBUF(KK))
      XDATA=SUM/0.8
C
C        ENTER NEW POINT INTO A SHIFT REGISTER
C
      DO 10 I=1,4
      L=5-I
10    DATA(L+1)=DATA(L)
      DATA(1)=XDATA
      JTEST=0
C
C        ARE POINTS ASCENDING OR DESCENDING ON CURVE?
      DO 20 I=1,4
      IF(DATA(I)-DATA(I+1))20,90,30
30    JTEST=JTEST+1
20    CONTINUE
      IF(JTEST)40,50,40
40    IF(JTEST-4)90,50,90
C
C        HAS A CHANGE OCCURED?
C
50    IF(JTEST-JTR)80,90,80
80    JTR=JTEST
      IF(JTR)100,100,110
C
C        IF MAX IS FOUND, CALCULATE INSPIRED VOLUME
C
100   VOL-CAL*(DATA(5)-XMIN)
      VOL=10.0*FLOAT(IFIX(VOL/10.0+0.5))
      IF9VOL.LE.40.0)GO TO 90
```

```
      IF(MOD(K,4Ø).EQ.1)WRITE(6,2Ø1)
      WRITE(6,2ØØ)K,VOL
      K=K+1
      TAVG-TAVG+VOL
      IF(ITIME)37Ø,371,37Ø
371   IST=ISEC
      ITIME=1
C
C        CALCULATE MINUTE VENTILATION
C
37Ø   IF(ISEC-IST-6Ø)38Ø,39Ø,39Ø
38Ø   VENT=VENT+VOL
      GO TO 9Ø
39Ø   IST=IST+6Ø
      VENT-VENT/1ØØØ.Ø
      WRITE(6,2Ø5)VENT
      AVG=AVG+VENT
      IND=IND+1
      VENT=VOL
      GO TO 9Ø
C
C        IF MIN IS FOUND, RECORD IT
C
11Ø   XMIN=DATA(5)
      GO TO 9Ø
2ØØ   FORMAT(3ØX,I4,8X,F6.Ø)
2Ø1   FORMAT(1H1,29X,22HBREATH    TIDAL VOLUME/1H )
2Ø2   FORMAT("ENTER CALIBRATION FACTOR")
2Ø3   FORMAT(F8.3)
2Ø4   FORMAT("ENTER TIME IN SECONDS")
2Ø5   FORMAT(/1ØX,"MINUTE VENTILATION =".F7.2,"  LITRES"/)
2Ø6   FORMAT(//5X,"AVERAGE MINUTE VENTILATION FOR",I3,"  MINUTES =",
     1F7.2,"  LITRES"///)
2Ø7   FORMAT(5X,"AVERAGE TIDAL VOLUME =",F7.Ø,"  MILLILITRES"///)
      END
      END$
```

APPENDIX IV

ALTERNATE TIDAL VOLUME MEASUREMENT

In the event that the laboratory computer is otherwise occupied, an alternate system has been designed for measuring tidal volumes. As before, an analog signal representing tidal respiration is obtained from the spirometer. This signal is converted to a four-digit BCD signal by a digital voltmeter[18]. An interface has been designed to allow the BCD output to be connected to a high speed printer[19]. The print command signal is generated by special circuitry included in the end-of-breath sensor. Both the upper and lower limits of each tidal breath are recorded on the printer. Tidal volumes can then be simply calculated as differences between adjacent readings.



18. HP model 5326B

19. Franklin model 1640